University College London
The Bartlett School of Graduate Studies

Mould growth and refurbishment of high-rise residential buildings

Georgios Smaragdis

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Abstract

High-rise residential buildings are among the dweeling types existing in the UK. Most of them have been built between the 1960's and 1970's abd they have poor environmental performance. High energy costs and mould growth are among the main problems that are encountered in these type of dwellings. The solution to deal with these problems is refurbishment. The most common method of refurbishment is overcladding of the external façade as apart from reducing the risk of mould and the energy costs, it also has the advantage of improving the external appearance of the building. In terms of cost, cavity wall insulation is the most efficient, however for buildings taller than a certain height a feasibility study should be conducted.

This study aims to investigate the factors that affect the risk of mould growth before and after the refurbishment of high-rise residential buildings. The focus is mainly given on four parameters: insulation, air permeability, use of trickle ventilators, and use of mechnical ventilation. A theoritical building was simulated to study the importance of each one of them.

The most effective way for the reduction of mould risk is the use of mechanical ventilation with heat recovery (MVHR) as it eliminates the risk of mould and simultanuously reduces significantly the energy demands for heating. The role of air permeability is also very important. The higher the air permeability, the smaller the mould risk is and vice versa. The use of insulation while reduces the energy demands it needs to be combined with some form of mechanical extract ventilation in order to have sufficient results. The use of trickle ventilators has only a small effect and this, ony when there is no insulation.

Acknowledgements

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1. Introduction

"Climate change is one of the most pressing issues on the world's agenda. In 1995 the Intergovernmental Panel on Climate Change (IPCC) concluded that the observed global warming could be attributed to increases in the carbon dioxide content of the atmosphere caused by human activities, and in particular industrialization and deforestation". (Garvin et al. 1998)

Climate change occurs as a result of the emission of greenhouse gases, such as carbon dioxide, resulting from human activity. The balance of carbon dioxide and other pollutant gases in the atmosphere has changed in a great extend as a result of the industrial activities over the last 200 years. The consequence is a net warming of the atmosphere leading to a change in weather patterns. The increasing deforestation and industrialization is considered to contribute essentially to the climate change. (Garvin et al. 1998)

The international debate over the need to move towards mitigating against climate change by reducing carbon dioxide emissions led to the Kyoto conference on 1995 where have been established targets for the reduction of such emissions. In the UK, the importance of energy efficiency in building design is constantly increasing as buildings make a significant contribution to the country's carbon dioxide emissions through energy used for heating, lighting and other services. (Garvin et al. 1998)

Improving the energy performance standards of new buildings is important but not enough. A dramatic change in replacement rates would be required for this to make a significant contribution to CO_2 reductions in the next 50 to 100 years. In Europe and in the UK the building stock has a long life and a very low replacement rate. Figure 1 presents data on change in the housing stock for the UK, Denmark, The Netherlands and Germany. It is obvious that replacement rates which are less than 0.1 % in combination with new building rates of over 1 % construction activity lead to a stock growth rather than replacement. (Bell 2004)

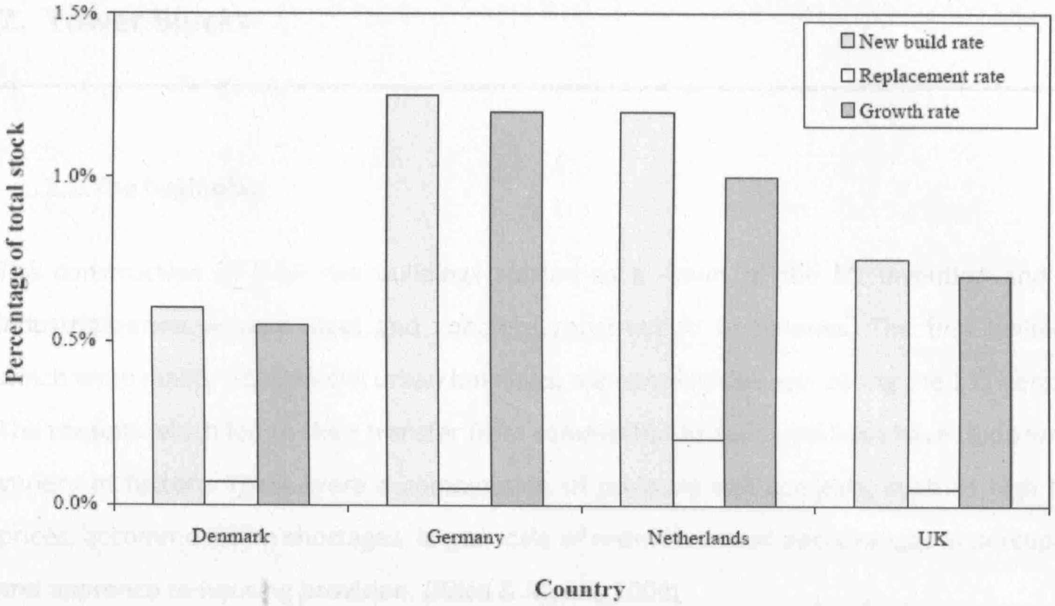


Figure 1: Housing stock change characteristics (Bell 2004, p. 3)

Given the evidence on replacement rates, there is no doubt regarding the importance of improving the energy performance of the existing housing stock if considerable amount of reduction in carbon dioxide emissions is to be achieved. (Bell 2004). One type of dwelling that can be encountered in the UK is tower blocks. Most of them being constructed in the 60's and 70's have poor environmental performance and consume high amounts of energy for heating, lighting, ventilation and other services. There are two ways to deal with this problem. The first one is to demolish the building and replace it with a more efficient one and the second is refurbishment.

The next section describes the history of tower blocks, the current context in the UK, and the environmental advantages related with their refurbishment.

2. Tower Blocks

2.1. The beginning

The construction of high rise buildings started as a result of the lift invention and the industrialization of new steel and concrete construction techniques. The first buildings, which were mainly commercial urban buildings, appeared in Chicago during the 19th century. The reasons which led to their transfer from commercial to residential use have to do with a variety of factors. These were a combination of pressure and contexts, such as high land prices, accommodation shortages, larger scale of redevelopment and changes in perception and approach to housing provision. (Price & Myers, 2004)

2.2. The rise

In the United Kingdom, the construction of high-rise residential blocks started after the end of the Second World War, with most of the buildings being constructed between 1949 and 1972. After the end of the war, the expected demographic growth, the increase in housing needs and the economic situation resulted to a high demand for new dwellings. During this time it was invented and developed the idea of tower block design and construction as a housing typology. This type of accommodation was considered as an easy way of quick and cost-effective construction of dwellings, combining the benefits of light, ventilation, green spaces, parking and urban locations availability. The technical and socio-psychological situation of that period was taken in consideration during the design process. The aim focused on unifying the physical fabric and meeting socio-political values such as equality, quality and peace. (Price & Myers, 2004)

The main driving forces that enabled the idea of high-rise living to be implemented include many aspects. As mentioned above, the use of concrete and steel in building construction made it possible to overcome previously insurmountable structural challenges of building high. Moreover, the attitude of local politicians encouraged and supported the implementation of this new typology as the reconstruction process had a positive effect not only in business and economy (large scale building activity) but in society as well (better living conditions). Large trades and projects as result of the increase in demand and construction activity were now commissioned by contractors while the role of supervisor of the projects was mainly held by architects and the local authorities. (Price & Myers, 2004)

2.3. The decline of tower blocks

The development of this form of living after the end of the Second World War was followed by their decline in the late 70's. Image and practical living conditions due to bad detailing, design and quality in combination with inadequate maintenance and polarized social grouping were the main reasons for the decline of high-rise housing. In addition to that, change of procurement method as a result of government change, led to new tendency towards private forms of housing management, promotion of house building and development and property ownership. (Price & Myers, 2004)

Problems related with inadequate heating systems, unreliable lifts, poor ventilation leading to condensation and mould, poor acoustic insulation, inappropriate use of materials (i.e. asbestos), difficulty in maintenance due to poor design and lack of community facilities were some of the defects that contributed to the decline of high-rise type housing. (Price & Myers, 2004)

In the late 1980's and in the early 1990's, many blocks were demolished after National Tower Blocks efforts. However, in late 1990's the option of refurbishment started to be more preferable than demolition. Interest of housing managers and professional groups was gradually revived by similar driving mechanisms as the post-war era. Due to high levels of urban densities, private developers started to consider high rise blocks as acceptable social forms and saleable to their markets. (Price & Myers, 2004)

2.4. Current context

In the UK, demands for new households are expected to present an average increase of 180,000 until 2011 (Barker 2003). This is mainly due to the different way of living in comparison with the past. The fact that nowadays people usually stay single for a longer time or they separate from their partners has as a result an increased demand for more small homes. Due to the fact that the UK is already crowded and intensely developed, the challenge is to provide the required amount of new homes and at the same time put effort to minimize the use of land. (Price & Myers, 2004)

2.5. Refurbishing high-rise residential buildings

Existing tower blocks are in need of urgent attention and refurbishment. In many cases though, the local authorities who mainly own this type of buildings, favor demolition. The fact is that sometimes refurbishment can be more expensive than demolition. However, from a long term perspective, keeping those tower blocks is a more efficient strategy than demolishing them. This is mainly related with the future demands for housing. By 2021, 3.8 million homes are going to be needed. (Migration Watch UK 2004). Consequently, the central and local government cannot afford to cut the 400,000 homes (Church, Gale 2000) which currently exist in tower blocks. Moreover, in terms of 'whole cost' economic efficiency and environmental impact, refurbishment seems to be a better solution than demolition.

The most important factors that determine the viability of a refurbishment are (Highfield 2000):

- the expected rental income (in developments for letting)
- the expected capital value (in developments to be sold after completion)
- the estimated cost of development
- the cost of acquiring the site
- the cost of financing the scheme

2.6. The environmental advantages

Since 1970, a major focus of concern with constantly increasing importance is the excessive consumption of energy in a global level and its related adverse implications, including global warming. Recycling and re-using existing resources as much as possible is one of the many ways in which worldwide energy consumption can be reduced. Whenever a building is recycled by opting for refurbishment rather than new build, a considerable amount of energy is saved by avoiding the need to extract raw materials and use them to construct a replacement building. 'Low-key' refurbishment, where most of the existing structure and fabric are retained, will clearly yield the greatest energy savings, but even the more drastic forms, where major alterations are made, will generally use less energy than demolition and new built. (Highfield 2000)

As regards with tower blocks specifically, they have some features that can be essential towards a sustainable development. Land use is kept to a minimum since tower blocks are a high density form of housing. Moreover, the potential for a smaller 'ecological footprint' is high. Good insulation in combination with the low surface area to volume ratio can contribute are essential features for a structure with reduced energy demands. Additionally, tower blocks are well suited to the application of combined heat and power schemes (CHP)

As mentioned before, condensation is one of the problems that are encountered in high-rise dwellings. The following section discusses the importance of the problem, the mechanisms behind condensation and the factors that affect it.

3. The problem of condensation

Condensation is a problem that millions of houses have to face in the UK every winter. About two million of them suffer from widespread dampness which often results in mould growth which affects not only the building itself as a construction but also the occupants' health. Condensation is less common in dwellings built after the mid-1980s and the Building Regulations can be considered accountable for that. The selection of right combination of remedial measures can play an important role during refurbishment of older properties in order to overcome the problem. However, condensation can even occur in and 'ideal home' and part of the remedy always lies in the responsibility of the householders. The adoption of suitable patterns of heating and ventilation by the occupants can contribute to the risk reduction of condensation and mould growth. (BRE 1997)

Condensation and mould growth are among the reasons which lead to the decision of refurbishing high rise housing. In an Information Paper, published by Building Research Establishment (BRE) (Trim, 1991) called 'Improving the energy-efficient performance of high-rise housing' are presented the results of a survey conducted by the Housing Studies Group at South London Polytechnic of high-rise blocks owned by 10 local authorities. The work was managed by the Building Research Energy Conservation Support Unit (BRESCU) on behalf of the Energy Efficiency Office (EEO). The survey represented 34% of high-rise blocks in the UK which included 1675 tower blocks with more than 83500 homes. Among the results if this survey was that 332 blocks of the sample, almost 20%, suffered from condensation problems. Most of these blocks had electrical heating and were lacking of insulation. Moreover, the results of the survey showed that the majority of the stock was lacking of thermal insulation. However, there was no evidence that there was any difference in the performance of those which had insulation and of those which did not.

3.1. The mechanisms of condensation

Air has the capability of containing a limited amount of moisture, usually as invisible vapour. The higher the air temperature, the higher the amount of water vapour it can contain before it becomes saturated and results to the appearance of water in form of liquid (Figure2). Vapour pressure of the mass of water per mass of air (kg_{water}/kg_{air}) is another way of expressing the amount of water vapour that can be present. (Trotman et al. 2004)

Two important parameters of water vapour in the air are relative humidity and the dew point temperature of the air. Relative humidity is the ratio of actual amount of water vapour present to the amount that it would be present if the air was saturated at the same temperature. It is normally expressed as a percentage. The importance of relative humidity can be realized by its effects. It determines the water absorption by porous materials and also it affects the growth of moulds and other fungi. It depends on both the temperature and the vapour pressure of the air and consequently can be modified by changing either or both of these. The dewpoint temperature of the air is the temperature where condensation of liquid water starts when air is cooled at constant vapour pressure. The dewpoint is expressed as temperature. However, it depends only on the vapour pressure as increasing or reducing the air temperature will make no difference to the dewpoint. (Trotman et al. 2004)

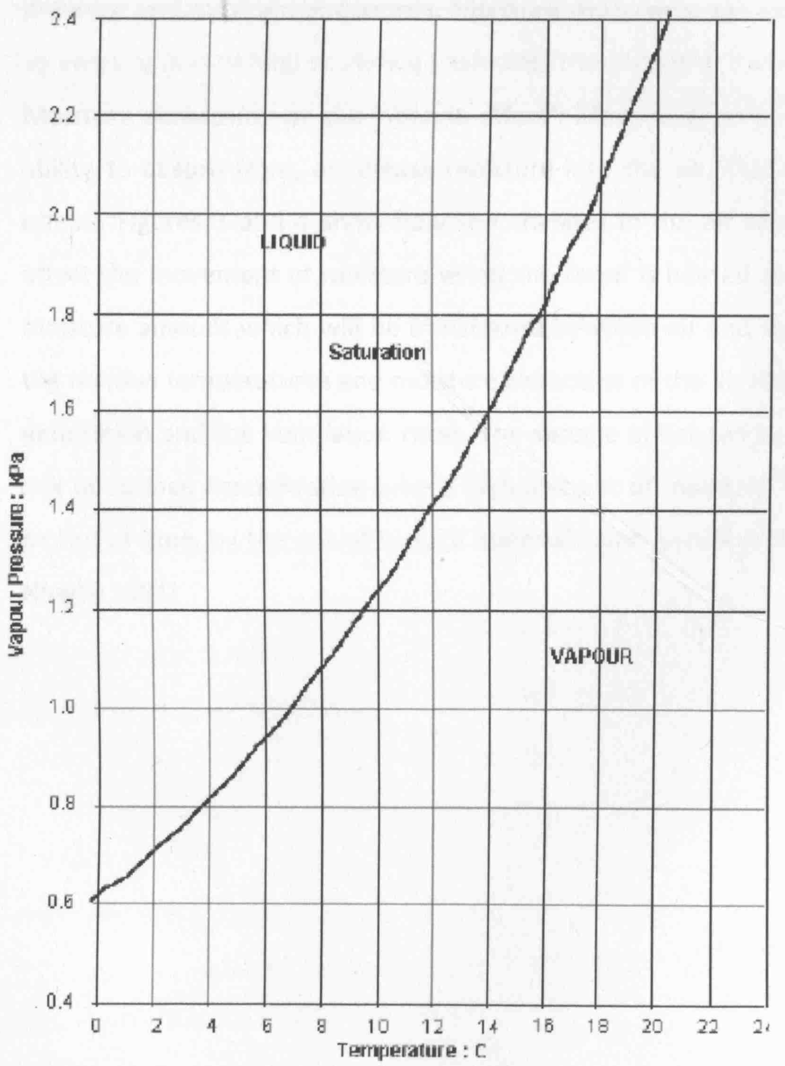


Figure 2: Saturation of air as a function of temperature (Trotman et al. 2004, p. 52)

3.2. The factors that affect condensation

The temperature and moisture levels of the air found in dwellings are the result of many different factors, each of which has a greater or lesser importance. These factors are:

- **Moisture generation**: People generate moisture in their homes. The number of occupants and the style of living are some of the factors that affect the produced amount of moisture. However, it is estimated that the typical activities of a household such as heating, cooking, washing and drying clothes can produce 7 to 14 liters of water each day (Garratt, Nowak 1991).
- **Moisture movement:** The generated moisture in a house will disperse to other areas either by diffusion, when the air is still, or by circulation caused by differentials in wind pressure and by thermal currents. Moisture movement can be at some extend control by opening (increasing) or closing (reducing) the windows. (Garratt, Nowak 1991)
- **Moisture absorption or the 'sponge effect':** Most kinds of building materials have the ability to absorb from, or release moisture into the air. This is known as the 'sponge effect'. Figures 3 and 4 show how the changes in the air temperature of a room will affect the movement of moisture when the room is heated and when it is cooled. The moisture amount which will be transferred between air and room surfaces depends on the relative temperatures and moisture capacities of the air and materials, the moisture generation and the ventilation rates. The sponge effect can be exploited to reduce the risk of surface condensation where high amount of moisture is produced over a short period of time, by the use of surface materials with high absorbency capacity. (Garratt, Nowak 1991)

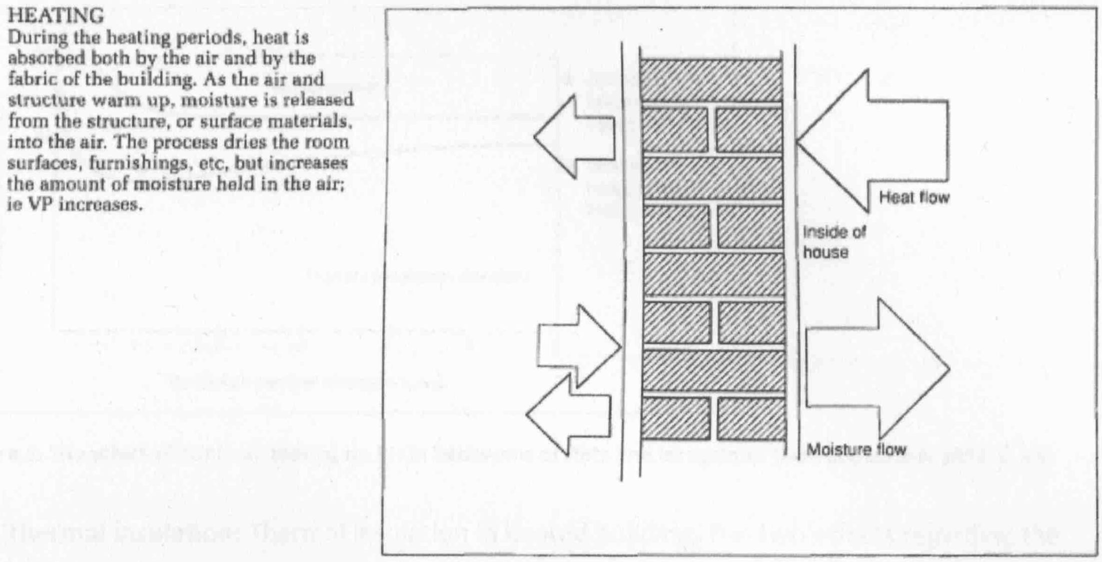


Figure 3: The effect of heating in moisture release (Garratt, Nowak 1991, p. 22)

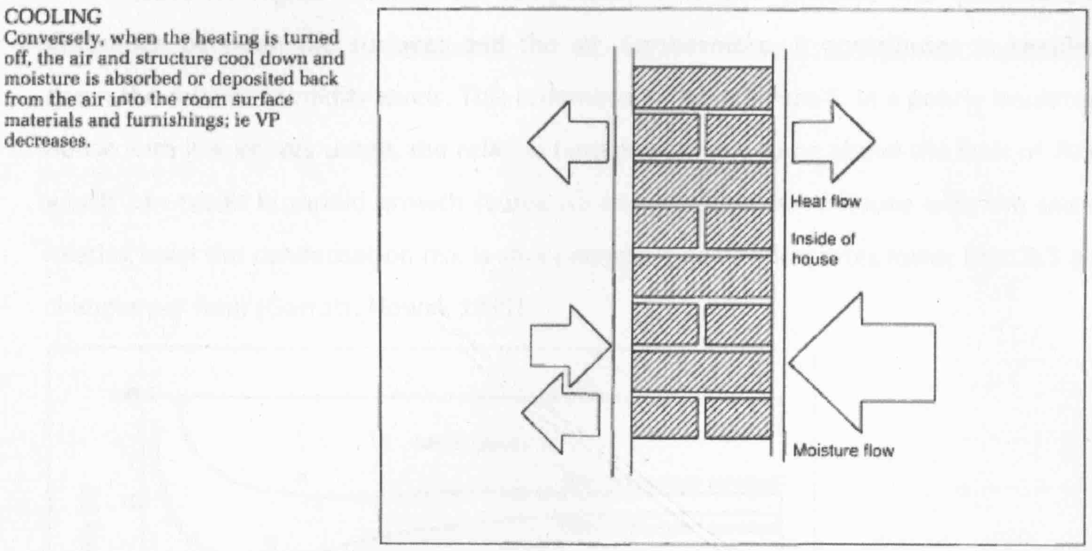


Figure 4: The effect of cooling on moisture release (Garratt, Nowak 1991, p. 22)

- **Heating:** In many houses only a small increase in heat is enough to control condensation. Figure 5 shows the effect of adding of an extra quarter of a unit of energy in the bedroom of a well insulated flat or bungalow. Without any heating provided, the high percentage of humidity may lead to mould growth regardless the ventilation rate and despite the fact that the room is insulated. By adding a minimal amount of heat this risk is avoided. (Garratt, Nowak 1991)

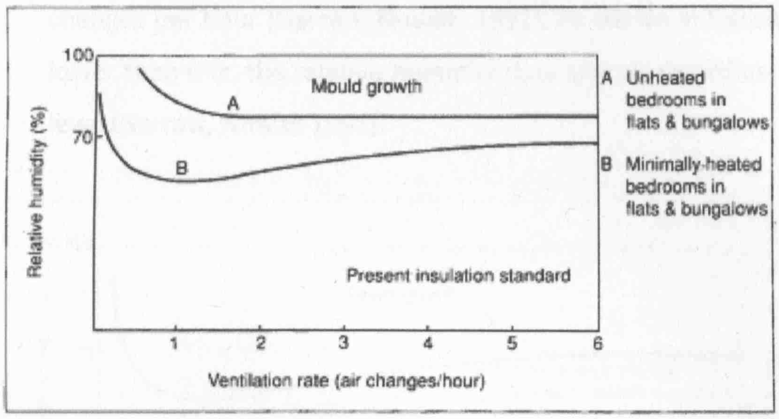


Figure 5: The effect of minimal heating on RH in bedrooms of flats and bungalows (Garratt, Nowak 1991, p. 26)

- **Thermal insulation:** Thermal insulation in heated buildings has two effects regarding the condensation control. Apart from reducing the heat losses from the building, something which leads to higher internal air temperatures, it also reduces the temperature difference between the surfaces and the air. Furthermore, it contributes in keeping down the relative humidity levels. This is demonstrated in Figure 6. In a poorly insulated house with low energy usage, the relative humidity is likely to be above the limit of 70% which can result in mould growth (curve A). In a well insulated house with the same heating level the condensation risk is small except at ventilation rates lower than 0.5 air changes per hour (Garratt, Nowak 1991).

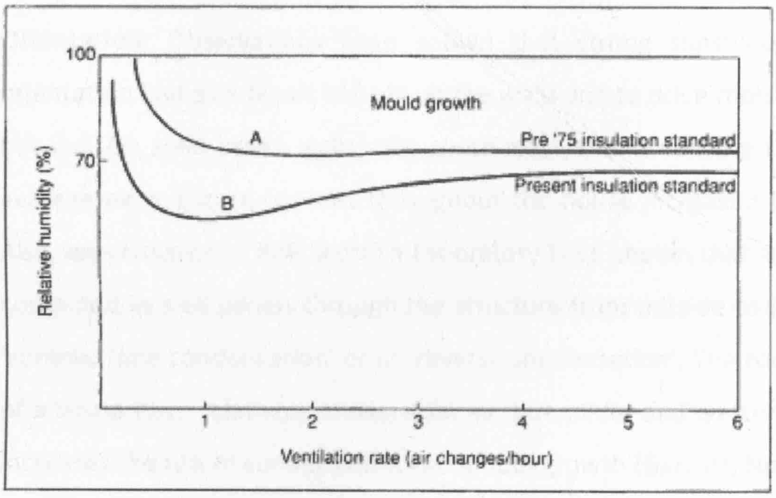


Figure 6: Comparison of relative humidity between poorly and well insulated houses (Garratt, Nowak 1991, p. 29)

- **Ventilation:** Ventilation is the main way to remove the moisture generated in a home. New built houses have lower background ventilation rates than older houses which are less air-tight. To prevent condensation, even in well insulated houses there must be sufficient level of ventilation. The ideal rate is somewhere between 0.5 and 1.5 air changes per hour (Garratt, Nowak, 1991). As shown in Figure 7, if the ventilation rate is lower than this, the relative humidity rises sharply regardless of heat input or insulation level (Garratt, Nowak 1991).

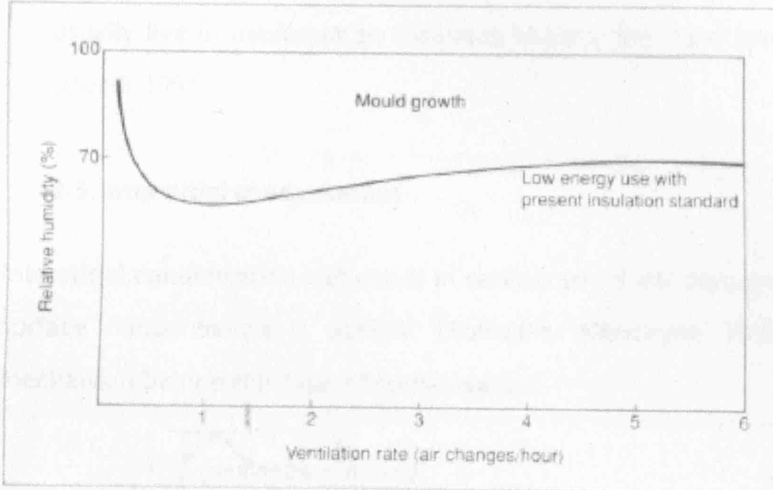


Figure 7: Relative humidity related to air change rates (Garratt, Nowak 1991, p. 35)

- **External conditions:** The external conditions affect the conditions within the house. The size of the effect depends on the air change rates and the time lag and insulation level of the building structure. Higher air moisture content in the external air will raise the background level of the moisture contained in the internal air (Garratt, Nowak 1991).
- **Orientation:** Observations have shown that strong sunshine on walls with south orientation had as a result to heat up the walls and to drive moisture out into the rooms beyond. On solid bricks walls with south-west orientation the results showed that the average air moisture content throughout the house increased by 8% during February. Also, experiments at BRE Scottish Laboratory have shown that sunshine drove moisture contained in wall panels through the structure from outside to inside. This is known as 'summertime condensation' or as 'reverse condensation'. The rooms on the shaded side of a house have relatively colder, drier air, but colder and wetter walls something which increases the risk of condensation and mould growth (Garratt, Nowak 1991).
- **The building:** The building acts as a buffer between the external and the internal conditions. Some building design factors which affect condensation include the construction materials, their durability, the plan form, the building type, the orientation, the location and the cold bridges (Garratt, Nowak 1991).
- **The occupants:** The occupants are the factor over which the designer has the less control. The factors which affect condensation risk and are related with occupancy

patterns include the size of the household, the lifestyle of the occupants and their income. The larger the size of the household and the more time is spent within the house, the higher the moisture production will be. Also, families with low income sometimes cannot afford the cost of adequate heating. This, in combination with they usually live in inadequately insulated houses, increases the condensation risk (Garratt, Nowak 1991).

3.3. Interstitial condensation

Interstitial condensation can result in serious structural damage and may occur even when surface condensation is absent. (Bullivant, Handisyde 1970). Figure 8 presents the mechanism behind this type of condensation.

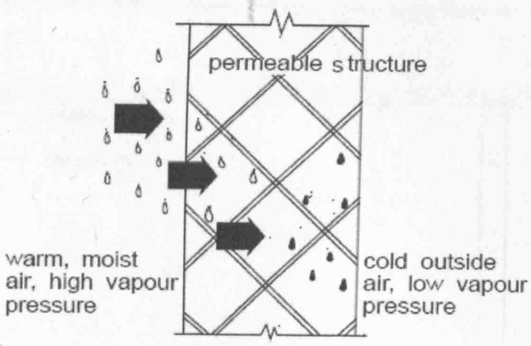


Figure 8: The mechanism of interstitial condensation (source: Timber Research and Devepolment Association (TRADAR), 1992, p. 1)

The vapour pressure difference created in a building by the generated water vapour drives the vapour through the material of the walls. The result is a gradient of vapour pressure, and therefore a dewpoint, through the structure, and a temperature gradient which depends on the distribution of thermal resistances. Condensation occurs when the temperature of the structure becomes equal with the dewpoint. If the main thermal resistance is on the warm side of the main vapour resistance, the temperature falls faster than the dewpoint and then they become equal. Figures 9 and 10 are showing the cross section of a timber framed wall with and without a vapour control layer (VCP) respectively. In Figure 9 where the VCP is incorporated between the plasterboard lining and the insulation, almost all the vapour resistance of the wall is on the warm side of the insulation, consequently the dewpoint is lower than the temperature through the whole wall. On the contrary, in Figure 10 almost all the thermal resistance comes from plywood sheathing on the colder side. The temperature falls rapidly in the insulation and becomes equal to the dewpoint on the inside surface of the sheathing, where severe condensation occurs. (Trotman et al. 2004)

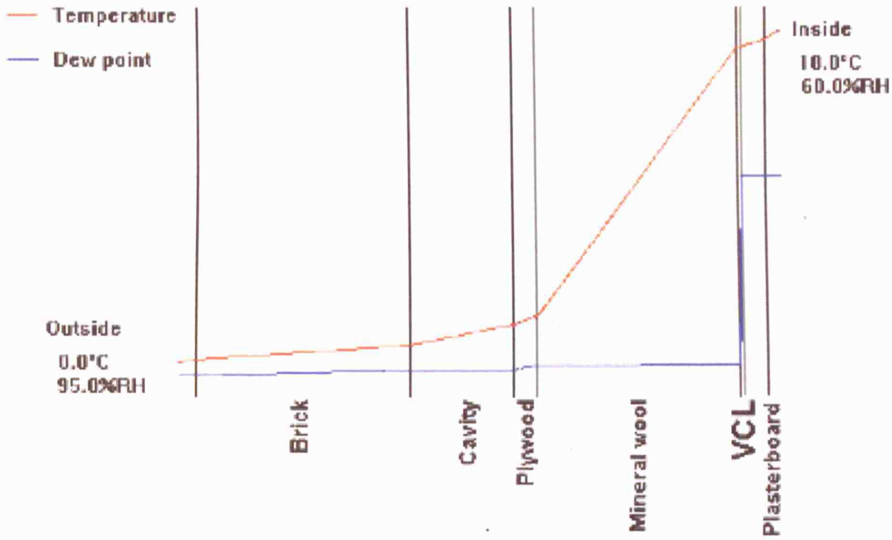


Figure 9: Temperature and dew point profile through a timber framed wall with a vapour control layer (Trotman et al. 2004, p. 61)

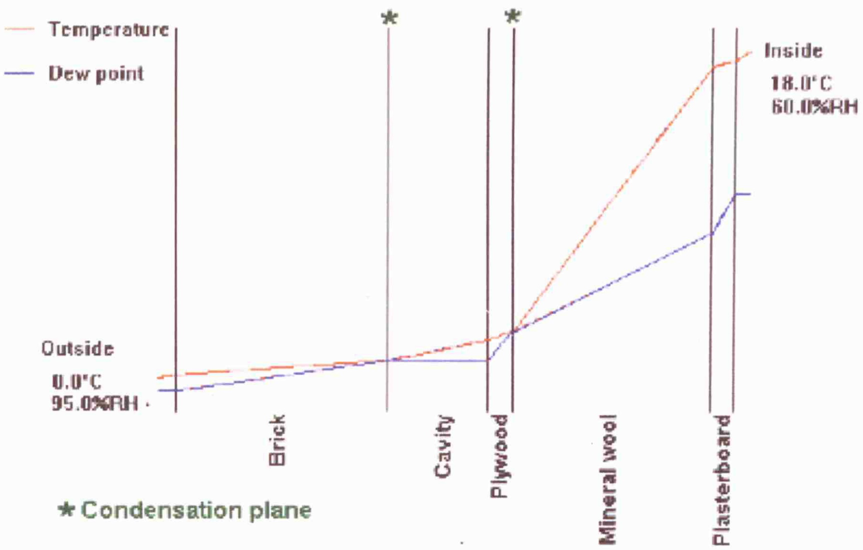


Figure 10: Temperature and dewpoint profile through a timber framed wall without a vapour control layer (Trotman et al. 2004, p. 61)

It should be mentioned here that sometimes interstitial condensation occurs when water vapour is diffusing in the interior of the building from outside. This is could be the case of an air-conditioned building located in a place with warm and humid weather. There are several examples of severe damage in air-conditioned buildings in areas such as the Middle East and the southern states of the USA. (Trotman et al. 2004)

Some of the effects of interstitial condensation include decay, accumulation of condensate which leads to increase of the thermal conductivity of the insulation, dimensional changes, migration of salts and liberation of chemicals. (Trotman et al. 2004)

4. Mould growth

Mould growth is often associated with surface condensation (Trotman et al. 2004). Condensation on surfaces such as tiles and glass is not considered very important by the occupants as it is not normally visible. However, this is not the case for mould. Complaints of 'dampness' and mould growth usually are combined. (Humphreys 1972)

Under extremely damp and unhealthy conditions mould will grow on any object in a room. However, moulds caused by dampness and condensation usually grow only on walls and surfaces. Mould, is more likely to grow in areas with stagnant air pockets such as corners or cupboards. It first appears in spots or small patches which will spread to form a grey green, black or brown layer. In their early stages mould spots are possible to be confused with dirt and can be cleaned off but they will appear again unless a fungicide is used. (Humphreys 1972)

4.1. The problem of mould growth in the UK

Condensation mould growth affects a high percentage of UK housing. In 1986, it was estimated by The English House Conduction Survey that a fifth of all households (almost three and a half million homes) experience some mould (Oreszcsyn 1992). The results of the English House Condition Survey in 1996, showed that 14.6% of dwellings had some degree of mould growth (Trotman et al. 2004). According to the same survey, the most severely part of the stock was the private rented housing (Figure 11). Also, 52% of mould problems occur in owner occupied housing (Figure 12).

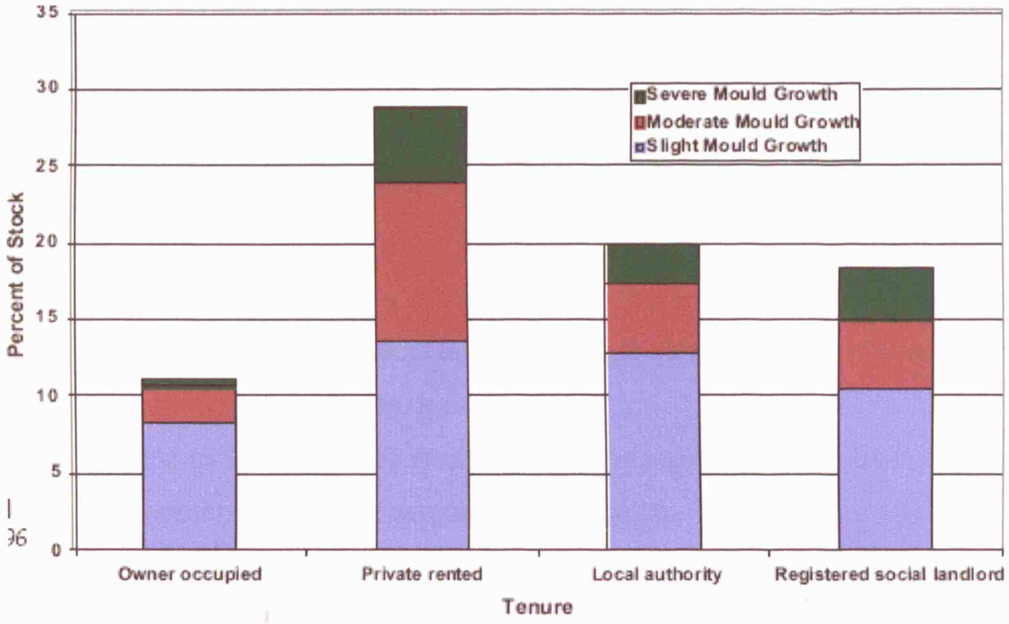


Figure 11: Incidents of mould growth by tenure (Trotman et al. 2004, p. 8)

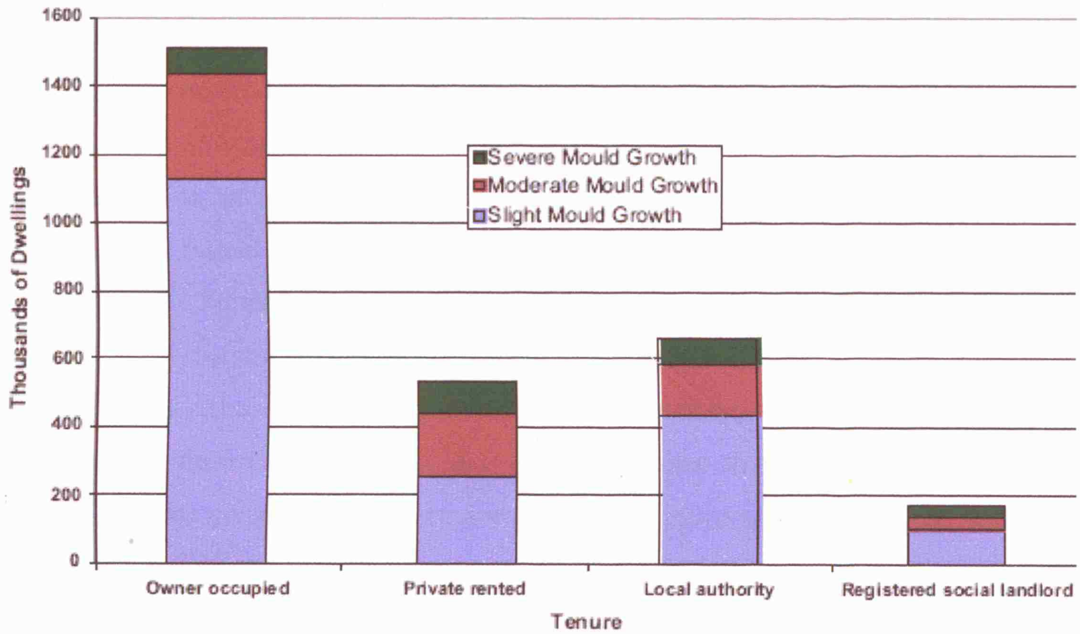


Figure 12: Numbers of dwellings with mould growth by tenure (Trotman et al. 2004, p. 8)

4.2. The causes of mould growth

According to Oreszczyn, (1992) the main requirements for mould to grow are:

- Mould spores which are always present in the air – there are several hundred per cubic meter even in the outside air, even in winter.
- Oxygen.
- Temperatures between 0°C to 40°C – there is an optimum temperature for individual species of mould but in practice all moulds will tolerate wall temperatures encountered in buildings, even freezing.
- Nutrients – even in well cleaned and maintained environments, moulds can thrive on nutrients present in dust and other deposits.
- Moisture.

The moisture content of the internal air is the critical factor which determines whether mould will grow in a dwelling. Moulds extract moisture from the substrate they are growing on which in turn extracts moisture from the surrounding air. Consequently, both the surface properties and the relative humidity are significant factors. Different levels of relative humidity are required for mould to grow on different materials. On hygroscopic materials such as wood and leather it can grow in a relative humidity of around 70%. For glass and ceramic tiles as well as other surfaces which do not absorb moisture, condensation is necessary for mould to grow. This happens at a relative humidity of 100%. The critical surface relative humidity for wall coverings such as plaster or wallpaper is 80%. If this level of humidity is maintained for several weeks then mould will grow. However, conditions in dwellings vary either because of the intermittent operation of the heating systems due to the varying external conditions or due to the moisture that is being introduced in the dwelling by the occupants presence and activities. According to a study by Adan (1994), mould will grow if the relative humidity is above 80% for the 50% of the time (Oreszczyn, Pretlove 2000).

4.3. The role of insulation in reducing the risk of mould growth

According to Oreszczyn (1992), in order to avoid mould growth at surfaces the relative humidity must be kept below 80%. However, mould will grow in a room even if the relative humidity is below 80%. This is explained by the fact that the temperature of the internal surface of an outside wall has higher relative humidity than the air in the room. Since cold air can hold more moisture than warm air, the reduction in air temperature close to external walls results in a higher relative humidity. Consequently, the general design guidance is that the room relative humidity should be kept below 70% Oreszczyn (1992)

The temperature difference between a wall without insulation and the air will be grater and hence the relative humidity of its surface will be higher, increasing the risk of mould growth. Insulation can reduce the risk mould growths by two ways. Insulated houses are cheaper to heat and so likely to maintain a higher temperature and hence a lower relative humidity. Furthermore, the temperature difference between the wall and the air temperature is reduced thus the relative humidity difference between the wall and the air is also reduced (Oreszczyn 1992).

Apart from the insulation there other means which can contribute in reducing the moisture production. These include the increasing of the heat input and the ventilation rate of the building.

4.4. Cold bridges and mould growth

According to BSRIA, cold bridging is a major cause of condensation and mould growth in buildings. (BSRIA 2005). In the Good Practice Guide 'Mimimising thermal bridging when upgrading existing housing' published by BRESCU (1996), thermal bridges are described as areas of the building fabric where, because of the geometry of the construction, heat flows are higher than through the rest of the building. The result is higher energy requirements and more importantly, lower internal surface temperatures and increased risk of mould growth. This can contribute to the increase of the building's energy consumption by increasing the internal temperature or the ventilation rates with the aim of reducing the risk of mould. (Energy Efficiency Best Pracrice Programme (EEBPP) 1996).

Figure 13: Signs of condensation and mould growth on a thermal bridge (Trotman et al. 2004, p. 56)

Thermal bridges can be categorized in two groups: repeating and non-repeating. Repeating thermal bridges have a significant effect on heat loss and they must be taken into account for the calculation of the U-values. They are rarely severe enough to make surface temperatures fall low enough to cause surface condensation and mould growth. Examples of these types of thermal bridges are timber joists, mortar joints, or mullions in curtain walling. Non-repeating bridges usually occur around openings such as lintels, at wall/roof junctions and where internal walls or floors penetrate the outer building fabric. They can add 10-15% to the total heat loss from the building. (Trotman et al. 2004)

The severity of a cold bridge can be characterized by the temperature difference ratio (TDR) (Oreszczyn 1992) a coefficient which shows how cold a surface is in comparison with the inside and outside temperature. The TDR is dimensionless, it takes values from 0 to 1 and it is given by the following formula:

TDR = (Internal air temperature-Cold bridge temperature)/(Internal air temperature- External air temperature)

The value of the TDR increases with the severity of the cold bridge. Cold bridges can be divided in four categories in relation with how serious they are (Table 1). Values of TDR greater than 0.3 are unacceptable because the cold bridge temperature will be lower than the surface temperature of double glazing, consequently condensation will occur on the cold bridge surface before it occurs on the surface of double glazing. Thus, condensation on the glazing will no longer act as an indication of dangerously high humidities. (Oreszczyn 1992)

Cold Bridge Category	TDR	Examples
Negligible	<0.15	Plain walls U-value less than 1.2 W/m^{2}K. External corners U-value less than 0.6 W/m^{2}K. Insulated lintels.
Moderate	0.15-0.2	Plain walls U-value greater than 1.2 W/m^{2}K. 3D corner U-value greater than 0.6 W/m^{2}K
Severe	0.2-0.3	External corners U-value 0.9 to 1.5 W/m^{2}K. Uninsulated lintels. Concrete party wall or floor.
Unacceptable	>0.3	2D corners U-value > 1.5 W/m^{2}K. 3D corners U-value > 1.0 W/m^{2}K. Party floor and wall drylined wall. Window reveal of drylined wall

Table 1: Severity categories for cold bridges (Oreszczyn 1992, p. 181)

Figure 14 compares the TDR for two corner constructions of an uninsulated wall and of an insulated cavity wall. The internal and external temperatures are 20 °C and 0 °C respectively. In both cases, the coldest surface temperature is occurring at the corner. For the uninsulated wall it is 9.1 °C while for the insulated is 17.1 °C. These temperatures correspond to TDR values of 0.54 (unacceptable cold bridge) and 0.14 (negligible cold bridge) (Oreszczyn 1992).

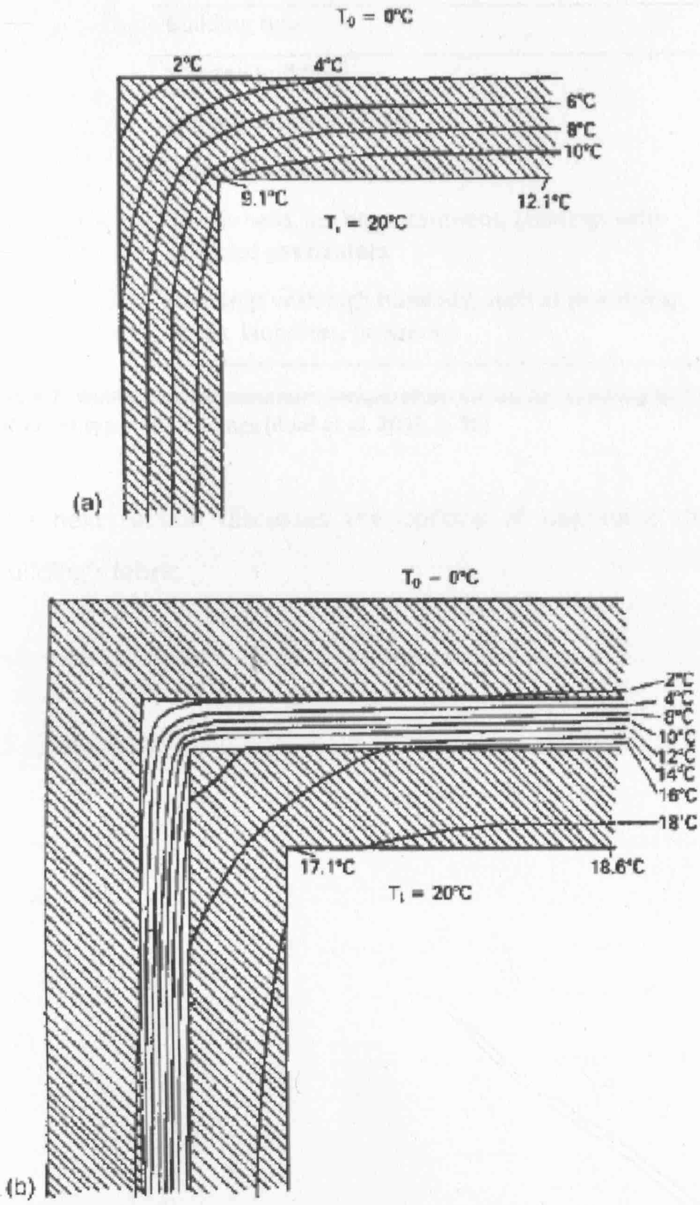


Figure 14: Isotherms and temperature difference ratio (TDR) at the corner of an uninsulated (a) and insulated (b) wall (source: Oreszczyn 1992, p. 182)

Apart from the temperature difference ratio (TDR) a different way of assessing the severity of a cold bridge is the surface temperature factor f_{Rsi} (Roaf et al. 2003). Temperature factor is calculated as:

$$f_{Rsi} = \frac{\text{Minimum internal surface temperature-external temperature}}{\text{internal temperature-external temperature}}$$

The lower the temperature factor, the higher the risk of condensation and mould growth. Table 2 presents suggested values of the temperature factor for different building types for avoiding condensation.

Building type	Minimum f_{Rsi}
Storage buildings	0.3
Offices, retail premises	0.5
Residential buildings, schools	0.75
Sports halls, kitchens, canteens, buildings with un-flued gas heaters	0.8
Buildings with high humidity, such as swimming pools, laundries, breweries	0.9

Table 2: Guidelines for minimum temperature values for avoiding surface condensation and mould growth in different types of buildings (Roaf et al. 2003, p. 86)

The next section discusses the options of upgrading the thermal performance of the building's fabric.

5. Upgrading the thermal performance of the building's fabric

In Britain 50% of the total energy is consumed by buildings (BRE 1999). The estimated energy waste per year in the UK is about £10 billion which is equivalent to half of the total value of output each year from the North Sea. One way of reducing the energy requirements of existing buildings is by minimizing the heat losses through the building's fabric including the windows. The easiest way to achieve this is by adding insulation on the external walls, on the floor and the roof of the building. In high rise housing the main attention is drawn on insulating the external walls as the roof and ground floor insulation affect only the adjacent spaces. The benefits of well-insulated buildings are increased thermal comfort, lower fuel bills, much reduced risk of condensation and mould growth, and lower maintenance costs and longer life (BRE 1999).

5.1. Insulation options

When adding or upgrading thermal insulation in existing walls there are three options: Internal insulation, external insulation, and in case of cavity walls, cavity insulation. Irrespectively the selected option, effort should be made to satisfy the current Building Regulations requirement for the U-value of the external wall which is 0.55 W/m^2K for cavity walls and 0.35 W/m^2K for other types of walls. (The Building Regulations 2000a). Although all three approaches achieve similar improvements in thermal performance, an inappropriate specification for a particular property may have serious implications for weather-tightness, durability, maintenance, and fire safety. Table 3 presents the advantages and disadvantages for each option. Also, Figure 15 presents a key decision diagram which illustrates the decision making process of selecting the most appropriate type of insulation.

Advantages	Disadvantages	Points to watch
Summary of advantages and disadvantages of cavity wall, internal and external insulation		
Cavity wall insulation		
Save up to 80% of heat loss	Cavity must be in suitable condition	Existing walls must be inspected
Cost advantage over internal and external options	Does not always cope well with thermal bridging	Choice of fibre, foam, beads or granules
Not disruptive	Limited scope depending on exposure zone	Plastics materials provide better insulation, but not necessarily better performance
Reduced condensation		Foam insulation may suffer from shrinkage and emit gases
Uses existing wall thickness		Plastic beads leave interconnected air paths so must include an adhesive
Internal wall insulation		
Good for solid walls where external systems are not possible, eg listed buildings	Slightly reduced room sizes	Face of wall should be well sealed
Good where cavity cannot be filled	Does not always cope well with thermal bridging	Vapour barrier essential
Good for adding insulation locally, eg to one room	Occupants must vacate rooms being treated during the work	Seal edges and service penetration points
Reduces thermal mass and improves responsiveness	Strict on-site quality control essential	Seal joints
	Skirtings, radiators and electrical points need refixing	Turn linings into the reveals and soffits of openings
External wall insulation		
Upgrades overall performance of wall	New weatherproof finish	Insulation must fit snuggly
Overcomes thermal bridging	Wall thickness increased	Finishes must be detailed
Moderates internal temperature swings	Cost	Cladding must include ventilated cavity
Little disturbance to occupants	Detailing around openings is critical	Render should be light coloured to prevent over-heating in summer
Internal services not affected	Rainwater goods need refixing	

Table 3: Summary of advantages and disadvantages of cavity wall, internal and external insulation (BRE 1999, p. 5)

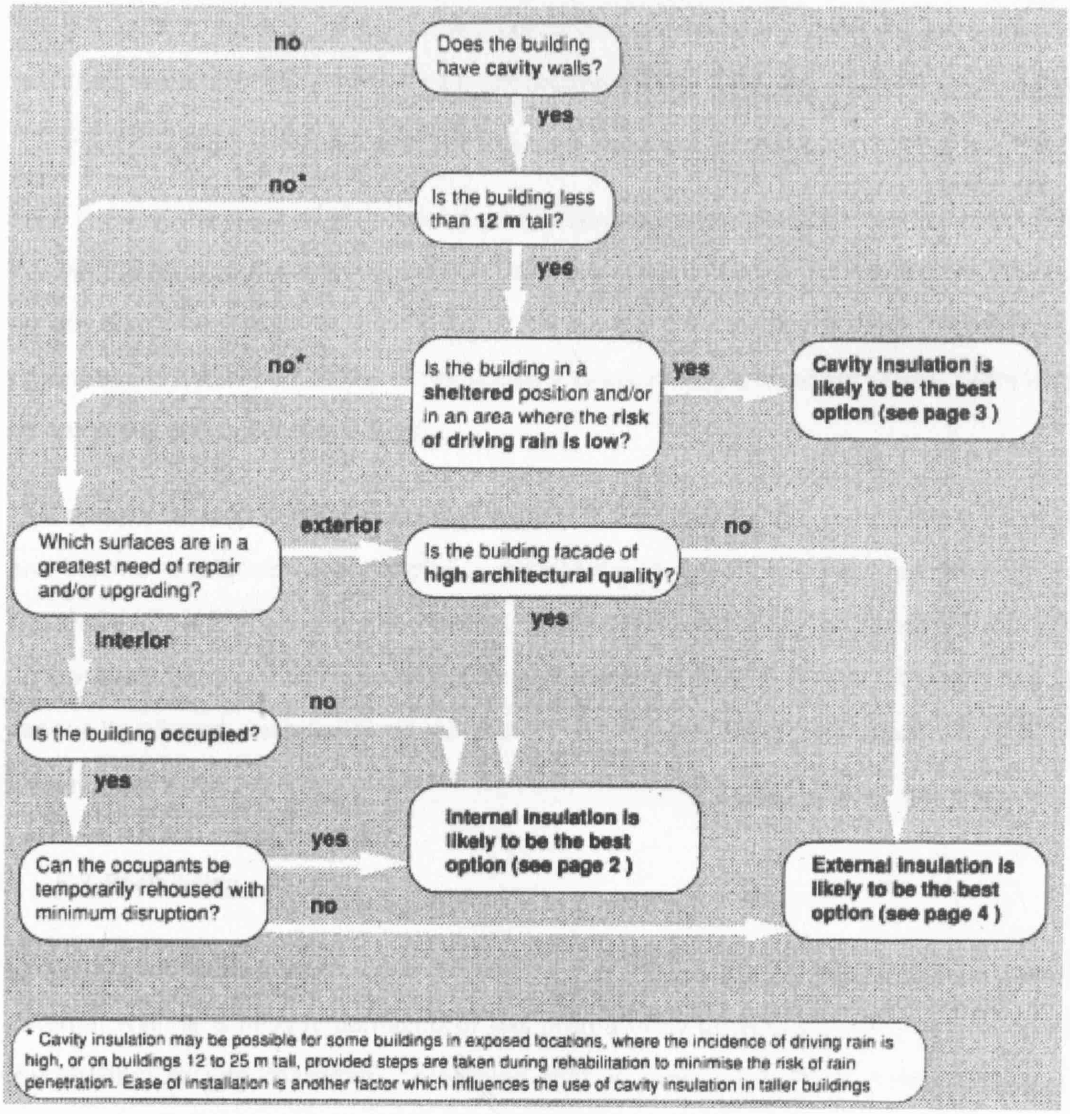


Figure 15: Key decisions in choosing the position of wall insulation (BRE 1990, p. 5)

Other factors that should be considered are the heating patterns as well as the thermal capacity of the walls. Internal insulation is more effective in buildings with intermittent heating since it prevents heat being absorbed by and lost in the walls, thereby giving a more rapid and warm period. However, when the space is not heated the surface temperature will be colder, increasing the risk of condensation on or in it. Therefore the existence of a vapour control layer on the warm surface of the insulation is vital to minimize this risk. When a building is continuously heated and consists of high thermal mass, the external insulation is preferred. The high thermal capacity walls absorb heat and emit it as the space temperature decreases. The risk of condensation is minimized. Externally applied insulation is effective with thinner walls as well regardless the heating pattern. (Highfield 2000)

Apart from the technical related issues, cost is also an important factor. Neither external nor external insulation are economically attractive unless they are part of other repair or rehabilitation work (Garatt, Nowak 1991).

With most of the stock of high-rise housing originating from the 1960's and 1970's in the UK, it is very likely that the building fabric would have required some refurbishment. The factors which affect the state of the building fabric are the quality of the construction, the maintenance and repair policy of the building landlord and the extent of vandalism imposed on the block. (Price & Myers, 2004)

The options of upgrading the fabric of high rise housing include overcladding, re-cladding, and internal insulation. Overcladding is the most common method as apart from upgrading the thermal performance of the building it offers the advantage of renewing the external appearance. Internal insulation is usually preferred in buildings where their external façade cannot be altered. Such buildings are those that are in a conservation area. (Price & Myers, 2004)

5.2. Recladding

Recladding or façade replacement is a relatively rare practice. It can occur however, if the external walling is heavily damaged or has prematurely deteriorated due to deficiencies in the original façade materials, something that is more likely to happen in lightly clad buildings. Other reasons are related with the desire of the owner to replace rather than overclad the existing envelope finish with something more attractive and durable. Recladding is also an option when overcladding is not feasible. For instance, in a building with a curtain walling system, overcladding is not possible because of the difficulties of attaching the new cladding to the existing glazed structure (Douglas 2004)

5.3. Overcladding

Overcladding can be considered as a new skin applied to the external walls of low or high-rise dwellings and it usually includes thermal insulation over the outside of the existing walls. It can extend to the whole of external walls or to particular elevations or parts of elevations. Windows may also be included in the overcladding. (Harrison et al. 1986)

The benefits of overcladding as a method of upgrading tower blocks include (Price & Myers, 2004):

- Restoration of existing façade
- Extending the life of the building
- Improved external appearance
- Thermal insulation and weather-tightness
- Improved acoustical performance of the building
- Lower maintenance cost

Figure 16 presents the socio-economic and environmental benefits of overcladding in relation with the cost, while Figure 17 presents the embodied energy of different cladding materials.

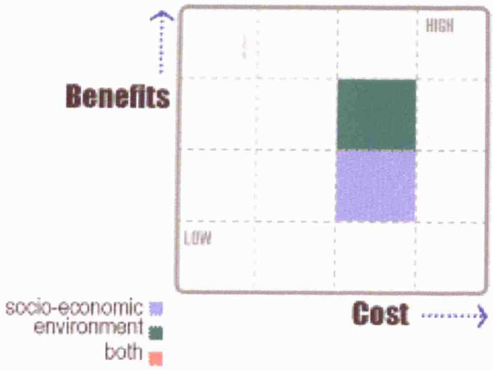


Figure 16: Socio-economic and environmental benefits in relation with the cost (Price & Myers, 2004)

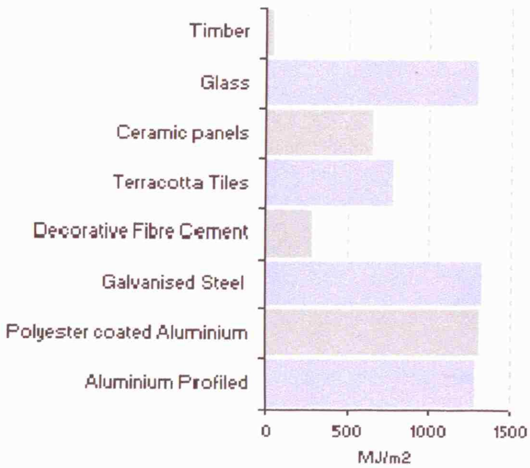


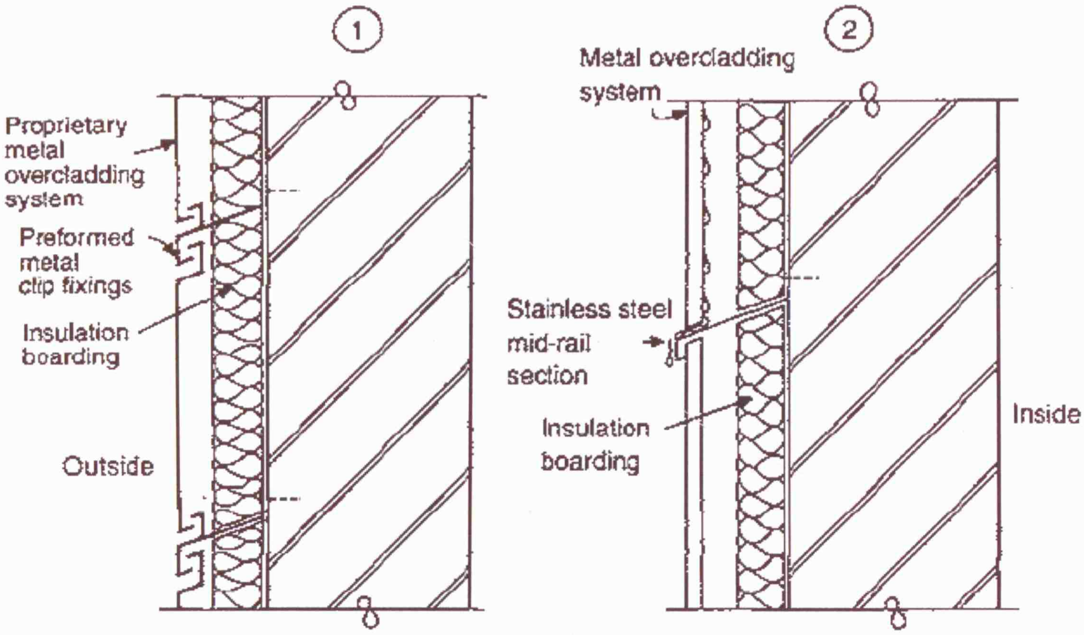
Figure 17: Embodied energy: Cladding (Price & Myers, 2004)

The cost of the overcladding varies and depends on the material used. Timber cladding on existing walls is from the cheapest options as it costs about 100/m^2. The cost for aluminum and galvanized steel cladding is about £200/m^2-£240/m^2 and £190/m^2-£220m^2. Finally terracotta cladding is relatively expensive as the cost varies from £350/m^2 to £400/m^2. All the prices mentioned above include 70-100mm external insulation. (Price & Myers, 2004)

Overcladding options for tower blocks include 'rainscreen' cladding and external wall insulation (brick-slip/render) systems (sometimes known as 'raincoat' systems).

5.3.1. Raincsreen cladding

Rainscreen cladding consists of a resilient outer screen, usually a decorative cladding panel supported on a vertical aligned sub-frame from timber, aluminum or steel. The sub-frame is fixed back to and supported by the primary building structure. A continuous void is maintained immediately behind the cladding panel and the entire system is ventilated at the base and head as well as at all penetrations (Price & Myers, 2004). There are two versions of this form of cladding. The traditional version is called 'drained and back-vented system'. The other is the 'pressure equalized system'. Both of them use a structural frame which supports an external panel and insulation. Figure 18 presents the two versions of rainscreen cladding.



Notes
1. Pressure-equalized rainscreen cladding.
2. Drained and back-ventilated rainscreen cladding.

Figure 18: 'Pressure equalized' and 'drained and back-ventilated' rainscreen cladding (Douglas 2004, p. 410)

Uninterrupted ventilation paths through the full height of the façade can assure the effective removal of any moisture penetrating through the various joints. The thermal performance of the structure can be enhanced by incorporating insulation into the cladding system, which in combination with breather membranes offers the advantage of eliminating cold bridges and interstitial condensation (Price & Myers, 2004). The insulation in a rainscreen system is usually positioned between the existing substrate and the ventilated cavity (Stirling 1999)

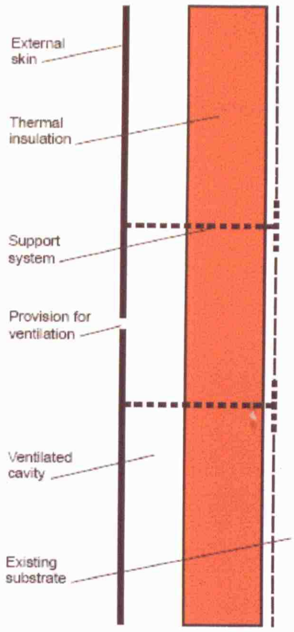


Figure 19: Rainscreen overcladding system (Stirling 1999, p. 2)

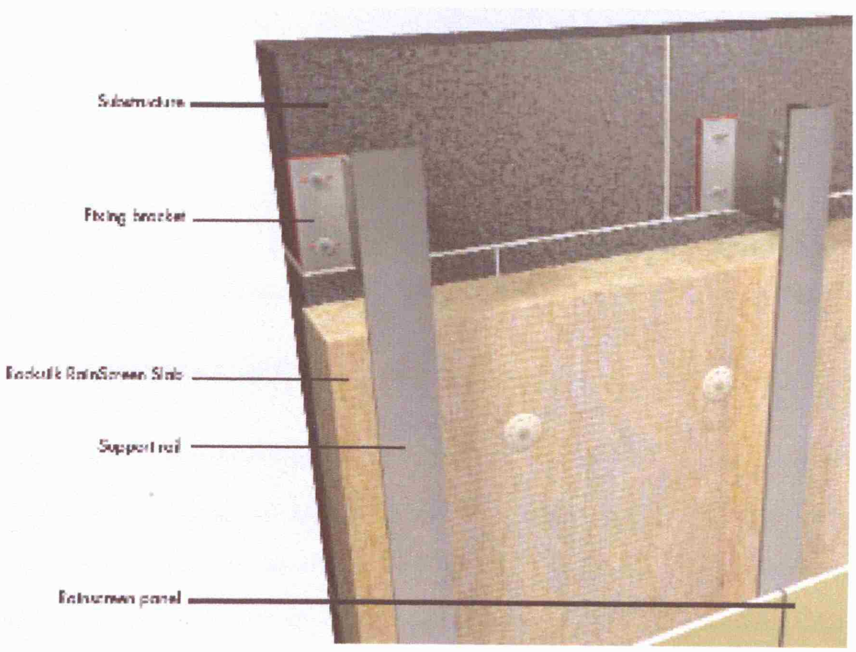


Figure 20: The Rocksilk Rainscreen Slab system, manufactured by Knauf (Knauf Insulation 2008a)

5.3.2. Rendered finish

This form of overcladding has a rigid slab insulation directly mounted or pasted on the external surface of the existing wall with an in-situ decorative coat of tender on the outside. (Price & Myers, 2004). In the UK it is the most common type of cladding. The main reinforcement used on the insulation to provide a key for the render is either a polyester or galvanized steel mesh, or lath.

Figure 21 presents the 'Rocksilk Krimpact Façade Slab', a mineral wool slab render insulation system manufactured by Knauf. The manufacture of the specific product has a very low impact on the environment and is classified as Zero ODP and Zero GWP according to 'Ecohomes' and 'Code for Sustainable Homes' classification.

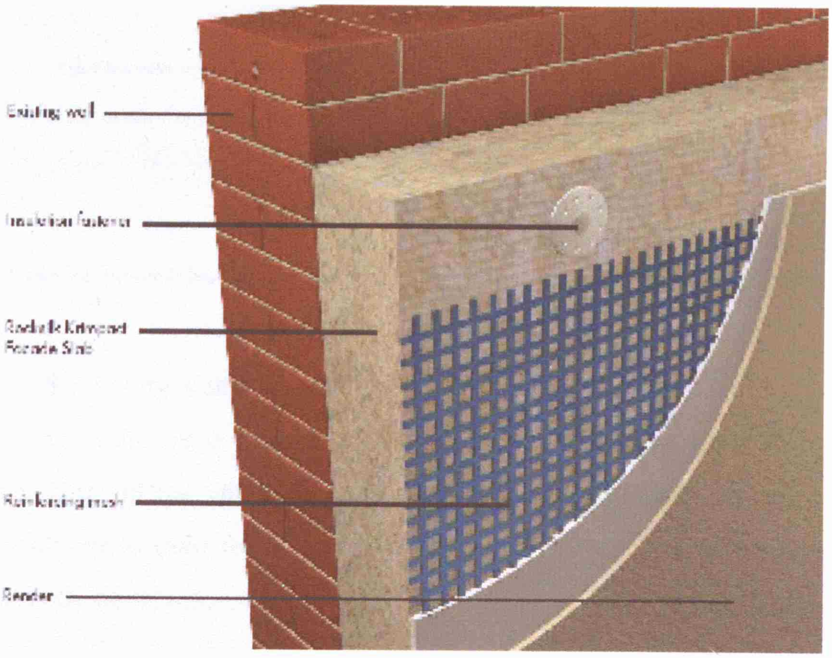


Figure 21: Rendered finish - Rocksilk Krimpact Facade Slab (Knauf Insulation, 2008a)

5.4. Internal Insulation

The use of internal insulation is mainly prefared for the improvement of the performance of historical buildings or of buildings that belong to a conservation area. According to the Energy Research Group at al. (1999 cited Douglas 2004) internal insulation is recommended only if the façade cannot be altered, the occupancy is not continuous or in cases where the simultaneous installation of the insulation is not possible for all the flats. Where internal insulation is applied, it is essential to have a control vapour layer at the warm side of the wall to avoid condensation. Also, careful consideration should be taken to avoid cold bridges and to reduce the air infiltration through cracks and gaps in the wall behind the insulation. (Knauf 2008b)

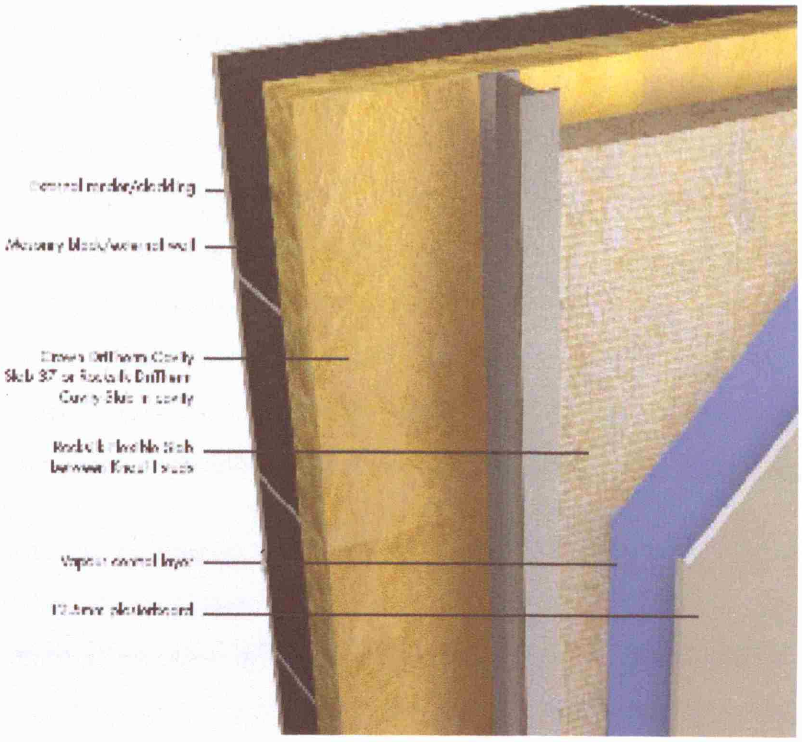


Figure 22: Internal insulation - Twin layer Crown DriTherm Cavity Slab 37 (Knauf 2008b)

5.5. Cavity wall insulation

Cavity walls were introduced in Britain in the early 1990. Currently, about 80% of all dwellings in the UK have cavity walls (DETR 1998 cited Douglas 2004). When cavity wall insulation is used for a refurbishment project it has the advantage that the insulation can directly be injected into the cavity and to improve significantly the thermal performance of the building's fabric (Knauf 2008c). Figure 23 shows the three different methods of insulating the cavity in a masonry cavity wall

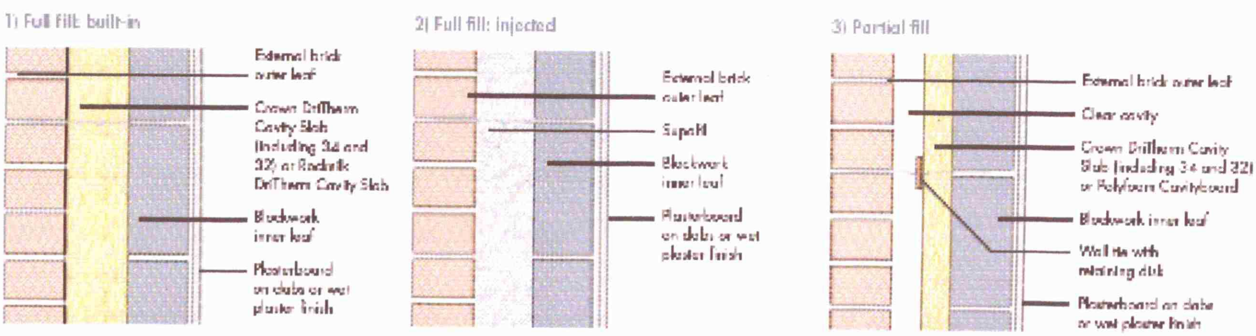


Figure 23: The three methods of insulating the cavity in a masonry cavity wall (Knauf 2008c)

The following section describes four refurbishment projects of high-rise residential buildings.

6. Case studies of high-rise housing refurbishment

The main reason for every refurbishment scheme is to improve the environmental performance of the building and to provide satisfying living conditions for the residents. The Borough of Camden is one of the London's Boroughs which has taken action towards the improvement of the energy performance of the existing housing stock under the 'Raising the standard' scheme which aims to bring all council homes o a good standard of external repair and to improve the environmental performance of the buildings. The estates most in need of repair receive the funding first, based on regular surveys of the conditions of the council's stock properties. It should be noted that Camden Council is spending an average of £45m per year on schemes to improve council property buildings. (Camden Council 2005)

The most common method of achieving reduced energy costs is by insulating the external fabric. As described in a previous section, there are three options: cavity wall insulation, internal insulation and external insulation. The criteria which the selection of each method is based on vary. According to Mr. Daniel White, from the Environment and Sustainability Team of Camden, cavity wall insulation is the first option as it is reduces rapidly the refurbishment cost (personal communication, July 18, 2008). However, before cavity wall insulation is applied, a survey has to be conducted as any defects in the walls will make them unsuitable for filling and could result in moisture from outside crossing the cavity through the insulation (Green Street 2003). Also, for buildings higher than 25 meters special assessment has to be undertaken (Housing Energy Efficiency Best Practice Programme 2002). According to Mr. White, internal insulation involves the implication of having people move out from their houses for the period of the refurbishment. This method is usually used in refurbishment schemes of social housing when the addition of insulation is done when the residents are absent, flat by flat. On the other hand, external insulation does not require the residents to move out from their houses and it has the additional advantage of improving the external appearance of the building. However, the cost is increased as apart from the insulation, there is also the cost of the scaffolding which can contribute essentially the total cost. (personal communication, July 18, 2008)

In the following sections are described some refurbishment projects of high-rise housing.

6.1. Chalcot estate

One of the refurbishment projects that have been carried out by the London Borough of Camden is the Chalcot estate refurbishment. The 1960s constructed estate consists of five tower blocks with 717 flats. The initial target was to achieve a 30% reduction in CO_2 emissions. This target was set after all the options in terms of cladding technology, heating, lighting and power loads were met. In order to meet the target of 30% the flats had to be brought up to a minimum National Home Energy Rating of 8. For a gas-heated home, an NHER rating of 10 corresponds to 2006 Building Regulations standard. The problems of the towers before the refurbishment had to do with poor thermal performance, condensation, mould growth, and poor thermal comfort levels. (Kenett 2008)

Initially the blocks had 25mm polystyrene insulation applied internally. The selected solution for the thermal improvement of the fabric was overcladding using an external aluminum rainscreen system. Overcladding was selected over the repainting or cleaning of the façade due to the need of improving the insulation and rain proofing. Also, the option of rendering was rejected because of discoloring and ongoing maintenance costs, escalates over the lifetime of the buildings, discounting the viability of this option. The windows were also replaced with double glazed argon-filled units with a U value of 1.2 W/m^2K. (Kenett 2008)

Blashford Tower, the first phase of the scheme was completed at the end of 2007. Work at the other blocks (Dorney, Burnham, Taplow and Bray) are at various stages and the target is to be completed in 2010. The average carbon savings per block are 178 tonnes a year. The total cost of the refurbishment is about £150m. (Kenett 2008)

6.2. Snowman and Casterbridge estates

Snowman and Casterbridge tower blocks were built in 1967 and 1968 respectively. Like Chalcot estate, the refurbishment was undertaken in order to improve energy efficiency and the external appearance of the blocks. An additional reason was to reduce noise for residents. The scheme included new windows and cladding (expanded polystyrene and rendering system). Also, work included repairs to the roof and to the boiler as well as internal redecoration of the communal areas. The cost of the scheme was £4.5m and it was also conducted by the London Borough of Camden. (Camden Council 2005)

6.3. Lodge Lane, Croydon

This project was carried out by the London Borough of Croydon and included the refurbishment of two 11 storeys blocks with 4 flats per storey. The flats were poorly insulated and consequently expensive to heat. Ventilation was provided by windows opening and by a common extract duct serving the bathrooms. In the kitchens there was no extract system. Apart from the poor energy performance, other problems that had to be tackled were condensation and dampness. (Best Practice Programme 1993)

Refurbishment work took place between November 1991 and November 1992. Weatherproof overcladding was chosen to improve the thermal performance of the fabric. The metal frame windows were replaced with PVC-U double glazed units. Regarding the ventilation system, separate mechanical ventilation systems with heat recovery (MVHR) were provided to each flat. The target wasR to achieve high air-tightness (0.25 ACH) and to provide some form of mechanical ventilation when required instead of using trickle vents. (Best Practice Programme 1993)

Monitoring of temperature and relative humidity were undertaken prior and after the refurbishment so as the benefits of the refurbishment could be determined. The function of the MVHR was also monitored. The result in terms of energy savings after the implementation of the whole package of measures was an average 37% reduction in energy consumption for the monitored flats. Apart from the reduced energy consumption, the level of thermal comfort was also significantly improved. (Best Practice Programme 1993)

Regarding the ventilation system, post refurbishment survey showed that in general, windows where opened less frequently by the tenants. However, windows in kitchen were still opened most of the days and those in lounges and bedrooms more than a week. The reason for this was mentioned to be too warm or stuffy air and the desire for fresh air to come into the dwelling. This indicated some general misconceptions about the purpose of the mechanical ventilation system. Further energy could have been saved if the importance of full airtightness had fully understood and windows were opened less frequently. (Best Practice Programme 1993)

In conclusion, the refurbishment project resulted in significant energy savings for the blocks of flats. The exact amount of savings varies for each flat due to different behavior of occupants, but on average the energy consumption was reduced by 37%. The savings from the MVHR units were only achieved due to the high air-tightness of the flats. What was highlighted from this case was the need for correct installation of those units as a major priority. (Best Practice Programme 1993)

6.4. Knowsley heights, Liverpool

Knowsley Heights is a group of three blocks located in the Huyton North housing area, 6 miles from Liverpool city centre. It was built in 1963 and the construction method was reinforced, cast in-situ concrete. External walls were 150 mm thick with a U-value about 1.7 W/m^2K making the flats expensive to heat, causing consequently acute problems of condensation, mould growth and thermal discomfort for the occupants. The flats had single glazed, metal frame windows and single glazed living room doors leading to external balconies. Heating was originally provided by an underfloor electric system which was replaced in the 1970s with electric night-storage heaters. (Best Practice Programme 1995)

The energy efficient measures adopted during the refurbishment project included, rainscreen overcladding with 100mm of mineral wool insulation, reduction in windows size and replacement of the units with double glazed ones, and trickle ventilators incorporated into the overcladding system. Also, it was installed electric total heating and mechanical ventilation with heat recovery (MVHR) system. (Best Practice Programme 1995)

The mechanical ventilation system extracts air from the kitchen and bathroom. It operates at trickle speed mode when it draws in air through the ventilators in bedroom window frames and at a higher 'boost' speed. This function is determined by a humidistat or manual switching and it draws air through the heat recovery unit, pre-warms it and distributes it to the living room and bedrooms through ductwork. (Best Practice Programme 1995)

After the refurbishment the internal conditions of the flat were significantly improved. Also, the savings in space heating in terms of energy cost were 36%. In a tenants survey after the refurbishment it was found that most of them were experiencing much better levels of thermal comfort, while the complaints for condensation problem reduced from 90% of the tenants to just one tenant who reported minor condensation problems. (Best Practice Programme 1995)

As regards with the cost effectiveness of the whole project the cost of the package was £915,000 (1989) with an 76,000 combined energy and non-energy saving per annum, giving a simple payback period of about 12 years. (Best Practice Programme 1995)

7. Aims and methodology of the study

As has already been mentioned above, the main problems that are usually met in existing high rise residential buildings is their poor energy performance, poor thermal conditions for the occupants and problems related with condensation and mould growth. The solution for dealing with these problems is refurbishment. Usually, a refurbishment scheme includes improvement in the building's fabric in conjunction with upgrading the building's services systems.

The present study aims to investigate the factors that affect the risk of mould growth in existing high rise residential buildings before and after their refurbishment. It should be noted here that refurbishment options related with the building's services systems have not been taken into consideration during the study. The main focus was given on the improvement of the thermal performance of the building's fabric.

The study was based on a theoretical seven storey building with a total height of about 20 meters. The effects of the following factors as regards with the risk of mould growth have been taken into consideration: insulation, air permeability, use of trickle ventilators and mechanical ventilation. Results have been drawn from all possible combinations of the different variables of the above factors. The assessment of mould growth risk was based upon the relative humidity levels of both the air and the walls' surface in a daily, weekly and monthly basis. Apart from the results for the risk of mould growth, the energy consumption was also taken into consideration.

Apart from the attributes of the building itself another important factor that influences the risk of mould growth in a building, is the occupants' activities and the moisture produced by them. Activities, such as cooking, bathing and washing of clothes are sources of high moisture production which result in increase of the relative humidities level. Consequently, a schedule of moisture production was used for a typical four member family. The results of moisture production were later converted to latent heat gains, since they affect the humidity levels of a space, and were used as input in the thermal simulation software.

8. Theoretical building model

8.1. General Information

The building consists of 7 storeys including the ground floor with 3 flats in each storey and is located in London. The main façade of the building has south orientation and its total length is 38 meters. The total area of each floor is 304m^2. The area of the windows in each flat is 20% of the corresponding floor area. They are located on the south and the north elevation of the building. Communal spaces occupy almost 13% of the total floor area of each storey.

The walls of the building are constructed by 250mm no fines concrete. Initially, there is no insulation and the windows are single glazed with wooden frame. The ground floor and the roof are also uninsulated.

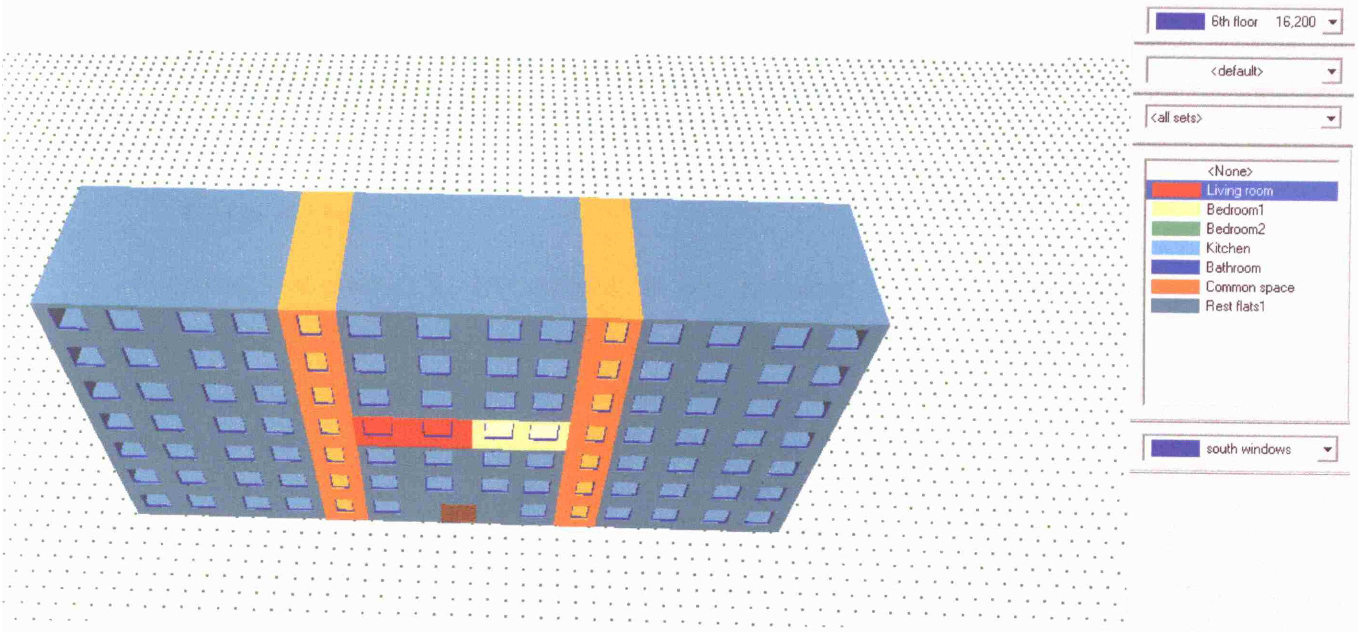


Figure 24: A three dimensional view of the building model

8.2. Parameters of the study

The parameters which were tested in order to assess the risk of mould growth were: insulation —no insulation, external insulation, internal insulation—, air permeability at 50 Pa pressure —20 m^3/m^{2}h, 10 m^3/m^{2}h, 5 m^3/m^{2}h—, use of trickle ventilators —without and with trickle ventilators— and use of mechanical ventilation —no mechanical ventilation, intermittent extract mechanical ventilation (IMV) for the kitchen and the bathroom, continuous extract mechanical ventilation (CMV) for the kitchen and the bathroom, whole flat mechanical ventilation with heat recovery (MVHR)—.

Parameter	Attributes	Specifications
Insulation	No insulation, single glazing	External Walls (U-Value-2.2 W/m2K): Plaster (13mm), Concrete (250mm)
	External Insulation, double glazing	External Walls (U-Value:0.45 W/m2K-in compliance with Part L of the Building Regulations): Plaster (13mm), Concrete (250mm), Mineral wool quilt (75mm), Plaster (13mm)
	External Insulation, double glazing	External Walls (U-Value:0.4 W/m2K-in compliance with Part L of the Building Regulations): Plaster (13mm), Extruded polystyrene, Air layer (25mm), Concrete (250mm), Plaster (13mm)
Trickle vents	Without Trickle Vents	No use of trickle vents
	With Trickle Vents	Equivalent area of trickle vents 40000mm2 in compliance with the Part F of the Building Regulations
Air Permeability (at 50Pa)	20 m3/m2h	0.25 air changes per hour
	10 m3/m2h	0.125 air changes per hour
	5 m3/m2h	0.0625 air changes per hour
Ventilation	No Mechanical Ventilation	
	Intermittent Extract Mechanical Ventilation (IMV)	Intermittent Mechanical extract Ventilation for the kitchen 60 l/s and the bathroom 15 l/s (minimum high rate) --- In compliance with the Part F of the Building Regulations
	Continuous Extract Mechanical Ventilation (CMV)	Continous Mechanical extract Ventilation for the kitchen 13 l/s and the bathroom 8 l/s --- In compliance with the Part F of the Building Regulations
	Whole Flat Continuous Mechanical Ventilation with Heat recovery	Whole flat Mechanical Ventilation with Heat recovery 21 l/s --- In compliance with the Part F of thr Building Regulations. The efficiency of thr heat recovery system was assumed to be 75%

Table 4: Attributes and specifications of each parameter of the study

8.3. Limitations

Regarding the refurbishment options, it was examined only the effectiveness of the insulation addition and of its position in terms of mould risk and energy consumption. The installation of mechanical ventilation which may be part of a refurbishment project was also examined without taking into account the energy consumed by the fans.

Moreover, it should be mentioned that the location of the simulated flat was on the 3rd floor and it is exposed to the external environment only from two sides (south and east). This had two effects on the results. The first is that if the flat was more exposed to the external environment (e.g. top floor corner flat) the resultant air changes per hour for the selected values of air permeability would be higher. The second is that the heat losses would be higher.

8.4. Moisture production

An important factor which affects the levels of the relative humidity in a dwelling is the moisture production by the occupants and their activities. Cooking, bathing and the washing of clothes are the main activities which result in high moisture production. The moisture production schedule was based on a 15 minute based moisture production schedule for a typical family leaving in a flat. Figures 25 and 26 present the moisture production schedule for a weekday and for a day of the weekend respectively for the whole flat, while Figures 27 and 28 present the same results for each room individually.

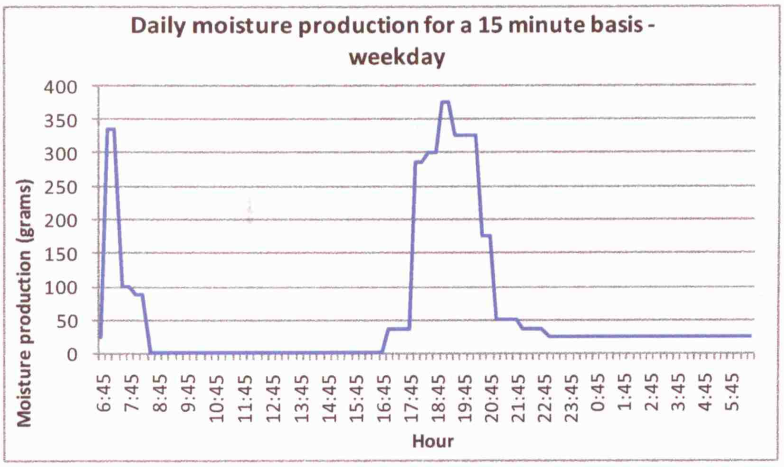


Figure 25: Total daily moisture production for a 15 minute basis – weekday

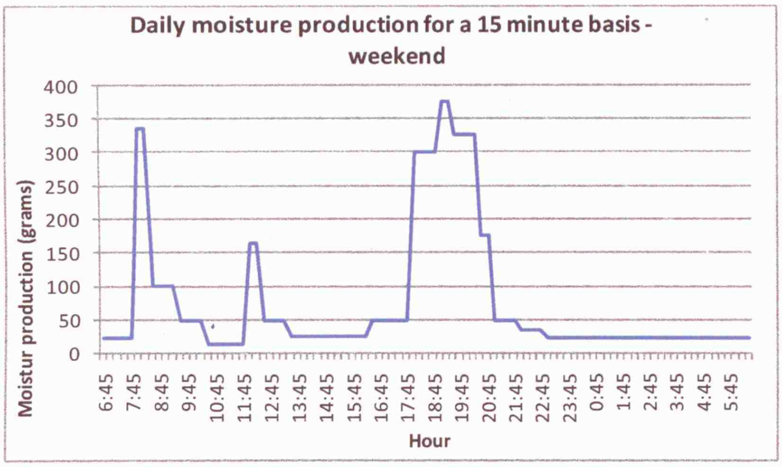


Figure 26: Total daily moisture production for a 15 minute basis – weekend

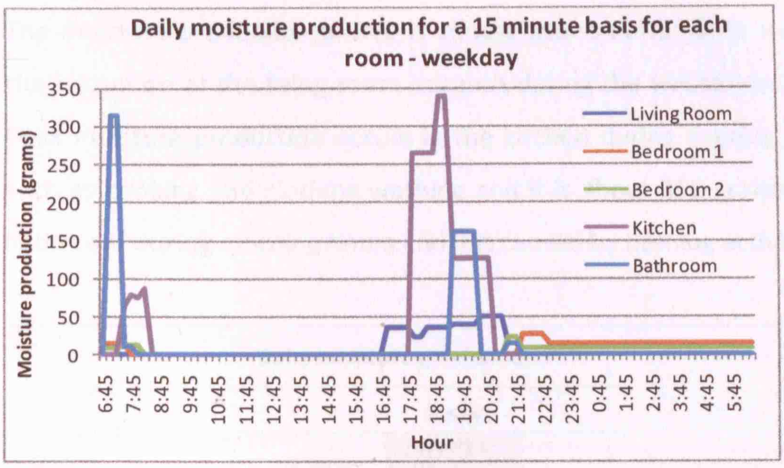


Figure 27: Daily moisture production for a 15 minute basis for each room

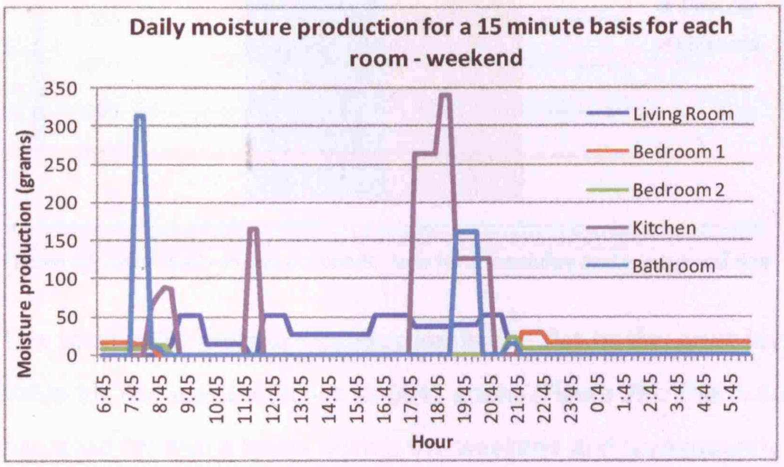


Figure 28: Daily moisture production for a 15 minute basis for each room

The moisture production profile is almost the same for both weekdays and weekend with the exception of the living room because during the weekends is occupied for more hours. Peak moisture production occurs in the kitchen during evening hours because of activities such as cooking and clothing washing and it is about 350 grams. The second peak is in the bathroom during morning hours and it is caused by bathing activities.

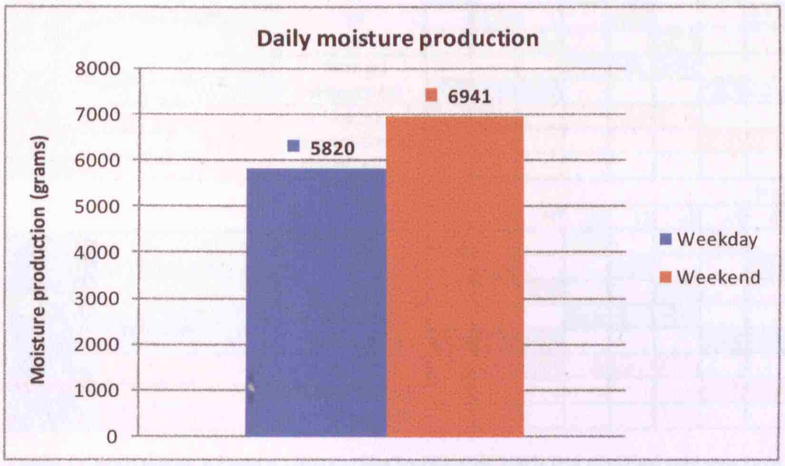


Figure 29: Total daily moisture production for a weekday and a weekend day

The total daily moisture production in the flat in the weekdays is 5820 grams, while this value for the weekend rises to 6941 grams (Figure 29). This is due to the fact that the flat is occupied for more hours during the weekend and consequently the moisture production is higher.

8.5. TAS simulations

The building was separated in 3 zone groups: flat, rest of flats, and common spaces. Zoning each flat of the building separately was considered to be unnecessary since examining the results of a typical flat is adequate for acquiring representative results. The selected flat for the study is located at the 3rd floor of the building, it has two exposed sides (south and north) and it accommodates a four member family (parents and two children).

As mentioned above, the parameters of the simulations were: insulation, air tightness, use of trickle ventilators, and use of mechanical ventilation. In total, 63 simulations were run. The 54 of them include all the possible combinations of the studied parameters excluding the use of MVHR. The rest 9 simulations included the use of MVHR. These simulations did not include the use of trickle ventilators.

Table 5 presents the value of each parameter for the first 54 simulations.

Number of simulation

			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
No Insulation	Air Permeability	20	■			■			■			■			■			■		
		10		■			■			■			■			■			■	
		5			■			■			■			■			■			■
	Trickle Vents	With (y)				■	■	■				■	■	■				■	■	■
		Without (n)	■	■	■				■	■	■				■	■	■			
	Mechanical Ventilation	No (n)	■	■	■	■	■	■												
		Intermittent (i)							■	■	■	■	■	■						
		Continuous ©													■	■	■	■	■	■

Number of simulation

			19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
External Insulation	Air Permeability	20	■			■			■			■			■			■		
		10		■			■			■			■			■			■	
		5			■			■			■			■			■			■
	Trickle Vents	With (y)				■	■	■				■	■	■				■	■	■
		Without (n)	■	■	■				■	■	■				■	■	■			
	Mechanical Ventilation	No (n)	■	■	■	■	■	■												
		Intermittent (i)							■	■	■	■	■	■						
		Continuous ©													■	■	■	■	■	■

Number of simulation

			37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54
Internal Insulation	Air Permeability	20	■			■			■			■			■			■		
		10		■			■			■			■			■			■	
		5			■			■			■			■			■			■
	Trickle Vents	With (y)				■	■	■				■	■	■				■	■	■
		Without (n)	■	■	■				■	■	■				■	■	■			
	Mechanical Ventilation	No (n)	■	■	■	■	■	■												
		Intermittent (i)							■	■	■	■	■	■						
		Continuous ©													■	■	■	■	■	■

Table 5: Attributes of each simulation in regards with the studied parameters

8.5.1. Internal conditions

According to CIBSE Guide A, internal heat gain is defined as: "the sensible and latent heat emitted within an internal space from any source that is to be removed by air conditioning or ventilation, and/or results in an increase in the temperature and humidity within the space".

The values for the sensible heat gains were taken from CIBSE Guide A. The degree of activity was assumed to be 'seated, very light work'.

While sensible heat gains affect the temperature of a space, latent heat gains have an influence on the relative humidity levels of that space as they affect the moisture content of the air. The values for the latent heat gain were estimated by the moisture production level in the flat, resulting from the occupants' activities by converting the moisture production within the flat into latent heat gain. For the conversion of the moisture to latent heat it was assumed that 0.5 kg of moisture is equal with approximately 300 Watts. The values for the lighting and the equipment gains were taken by the TAS internal conditions database.

Figures 30 and 31 present the occupancy schedule for each space in a 15 minute basis. This schedule was used not only for the occupants' heat gains, but for the lighting and equipment gains as well.

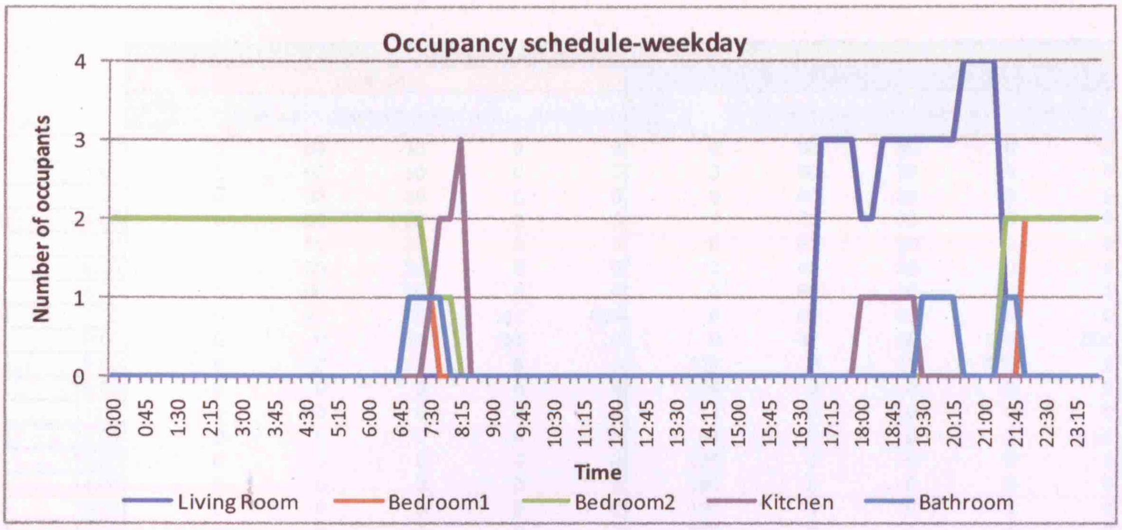


Figure 30: Occupancy schedule (weekday)

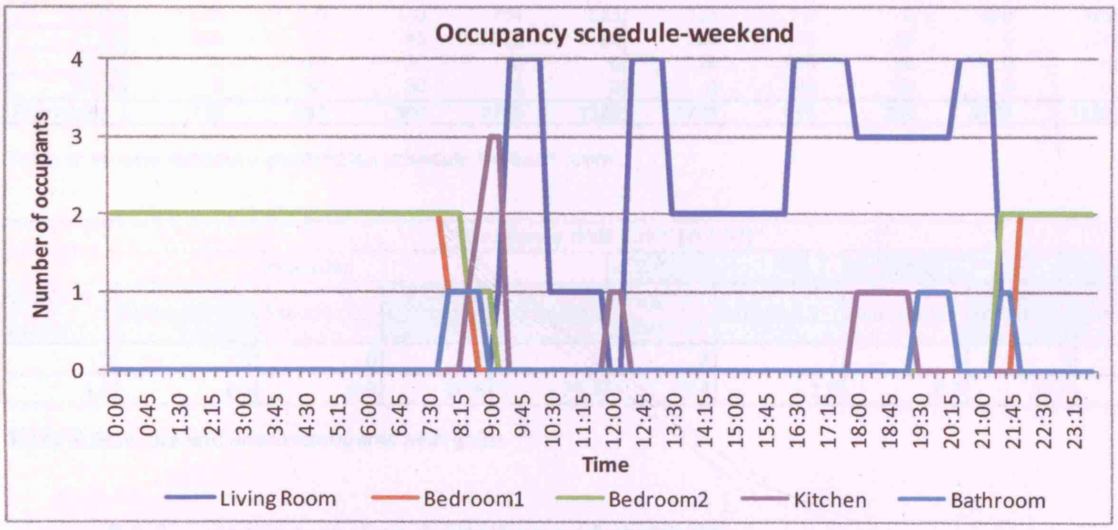


Figure 31: Occupancy schedule (weekend)

Here, it should be highlighted the fact that the occupancy schedule and therefore the internal gains schedule were based on a time period of 15 minutes and had varying values. However, in TAS the schedule is based on an hourly basis and as input can be used only one value. In order to overcome this problem initially it was estimated the moisture production over an hour by adding the moisture production of the 15 minutes time period for each hour (Table 6). Afterwards, it was estimated the average value of moisture production but only for the hours that there was moisture production. For instance, for a weekday there is moisture production in the living room for the hours 17:00 to 21:00. As input in TAS, was used the average value of the moisture production only for those hours and not the average value over a 24 hour period. This approach which had to be adopted for the simulation purposes could cause some inaccuracy, since using an average value does not correspond to the fluctuations of the moisture productions (Figures 27, 28).

	Moisture Production gramms/hour									
	Weekday					Weekend				
hour	Living Room	Bedroom1	Bedroom2	Kitchen	Bathroom	Living Room	Bedroom1	Bedroom2	Kitchen	Bathroom
0:00	0	60	30	0	0	0	60	30	0	0
1:00	0	60	30	0	0	0	60	30	0	0
2:00	0	60	30	0	0	0	60	30	0	0
3:00	0	60	30	0	0	0	60	30	0	0
4:00	0	60	30	0	0	0	60	30	0	0
5:00	0	60	30	0	0	0	60	30	0	0
6:00	0	60	30	0	0	0	60	30	0	0
7:00	0	41	38	141	650	0	60	30	0	0
8:00	0	0	11	161	0	0	41	38	141	650
9:00	0	0	0	0	0	114	0	11	175	0
10:00	0	0	0	0	0	128	0	0	0	0
11:00	0	0	0	0	0	55	0	0	0	0
12:00	0	0	0	0	0	64	0	0	0	0
13:00	0	0	0	0	0	175	0	0	0	0
14:00	0	0	0	0	0	100	0	0	0	0
15:00	0	0	0	0	0	100	0	0	0	0
16:00	0	0	0	0	0	100	0	0	0	0
17:00	145	0	0	0	0	200	0	0	0	0
18:00	118	0	0	264	0	173	0	0	1055	0
19:00	150	0	0	1130	323	145	0	0	928	323
20:00	178	0	0	714	323	155	0	0	500	323
21:00	128	0	45	375	28	200	0	45	0	28
22:00	0	110	30	0	0	28	110	30	0	0
23:00	0	60	30	0	0	0	60	30	0	0
Total daily	718	631	364	2785	1323	1735	691	394	2799	1323

Table 6: Hourly moisture production schedule for each room

	Occupancy Heat Gains (W/m2)									
	Weekday					Weekend				
	Living Room	Bedroom1	Bedroom2	Kitchen	Bathroom	Living Room	Bedroom1	Bedroom2	Kitchen	Bathroom
Sensible	9	6	6	5	6	8	7	6	5	6
Latent	4,0	1,9	0,9	20,6	28,3	3,4	1,9	0,9	24,9	37,0

Table 7: Sensible and latent occupants heat gains

8.5.2. Heating, cooling, infiltration and ventilation

For the heating period, the thermostat was set at 20 °C for all the spaces of the flat. During the summer period, there is no mechanical cooling, while ventilation occurs naturally by the opening of the windows. The windows start to open at 24 °C and are fully open at 26 °C. If the external temperature is higher than the internal then they close.

Infiltration rates or air permeability was one of the parameters of the study. The values of air permeability that were used for the simulation purposes were 20 m^3/m^2h, 10 m^3/m^2h and 5 m^3/m^2h at 50 Pascal. The corresponding values in air changes per hour were 0.25 ach, 0.125

ach and 0.0625 ach. It should be mentioned that even when the value of air permeability is high, the infiltration rate in air changes per hour is low. This is due to the fact that the flat has only two exposed sides (south and north).

9. Mould risk assessment

The criterion which was used to asses the risk of mould growth was the relative humidity of the air and of the internal surface of the external walls.

The relative humidity results from TAS simulations were adjusted in order to take accound the 'sponge effect' which is 'the ability of the fabric of a building and the building contents to absor and desorb water vapour'(British Standards Institution (BSI) 2002. These values of the 'damped' relative humidity were finally used to evaluate the risk of mould growth.

9.1. Mould risk criteria

The main citerio which was used to assess the risk of mould growth was the level of the relative humidiy. Both air and surface relative humidity were calculated. Apart from assessing the risk of mould growth, the surface relative humidity was also used to investigate the effects of the insulation position in terms of mould growth. Consequently, the surfaces of which the relative humidity was calculated, were the internal surface of the external walls.

The values that were used in order to evaluate the risk of mould growth were the average daily, weekly and monthly relative humidity. The critical air relative humidity above which there is risk of mould growth was 90%, 79% and 70% (International Energy Agengy (IEA) 1990) for daily, weekly and monthly basis respectively. The corresponding values for the surface relative humidity were 99%, 89%, and 80% (IEA 1990).

9.2. Mould risk assessment of the living room and the bathroom using air's relative humidity criterion

The following figures display the daily, weekly and monthly mould risk for the living room and the bedroom in order to investigate the effects of air permeability, insulation, and trickle ventilators on mould risk. No mechanical ventilation is used.

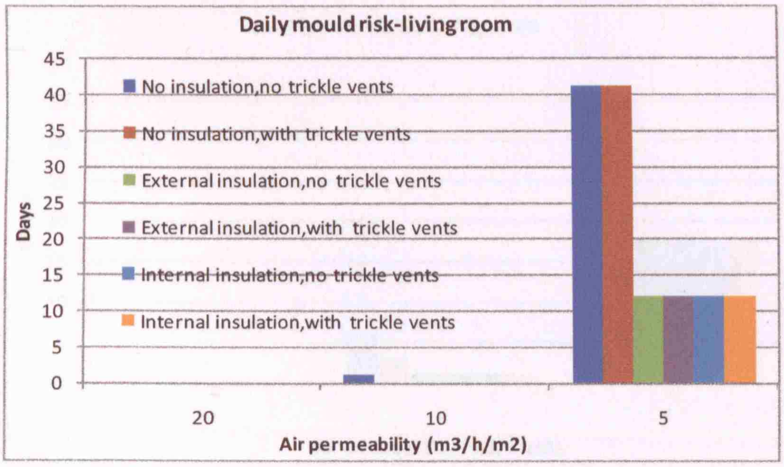


Figure 32: Daily mould risk – living room

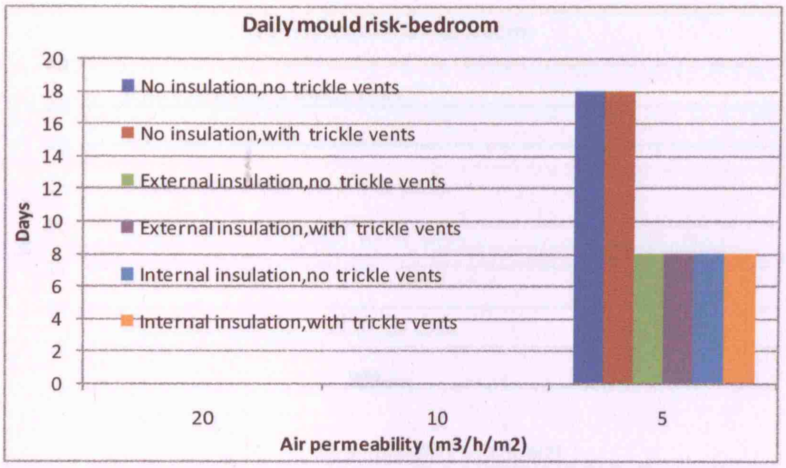


Figure 33: Daily mould risk - bedroom

For 20 m^3/m^2h air permeability there is no mould risk for all the cases. The same happens for 10 m^3/m^2h air permeability with a very low risk of mould growth in the living room for the case where there is no insulation. For the value of 5 m^3/m^2h, there is mould risk for all the cases. This is higher when there is no insulation, while for the rest of the cases the risk is the same regardless the use of trickle ventilators or not, and regardless the position of the insulation.

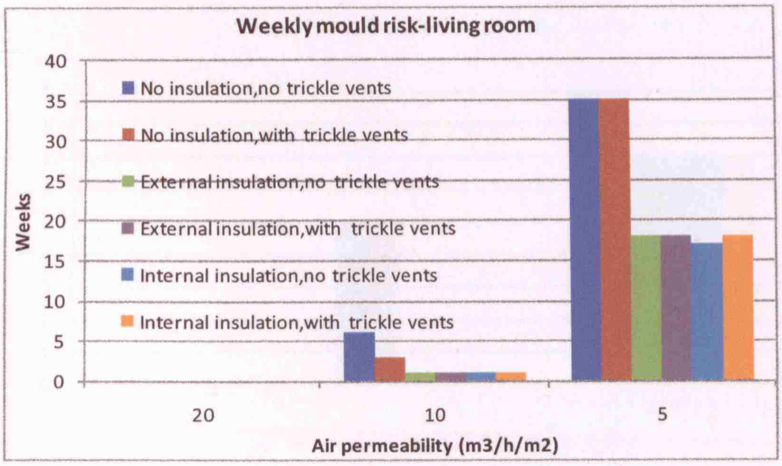


Figure 34: Weekly mould risk – living room

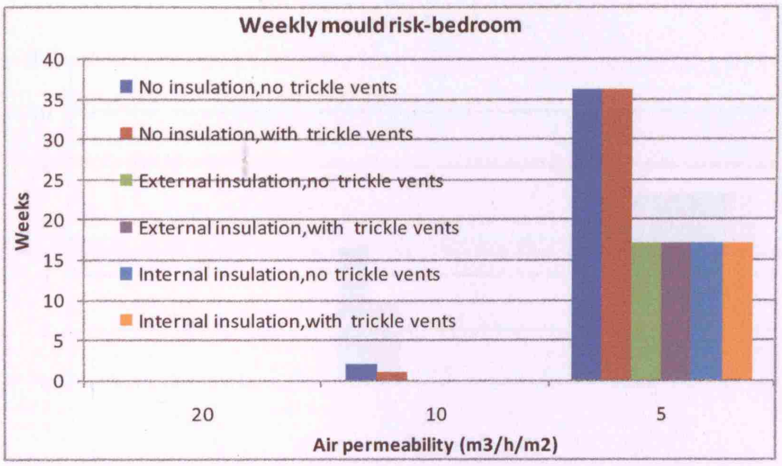


Figure 35: Weekly mould risk – bedroom

The figures regarding the mould risk in a weekly basis are similar with those in a daily basis. The weekly mould risk is a little higher in the living room than the bedroom for 10 m^3/m^2h air permeability. Regarding the effectiveness of trickle ventilators they have only a small effect in the reduction of mould risk, but only for medium values of air permeability $10m^3/m^2h$.

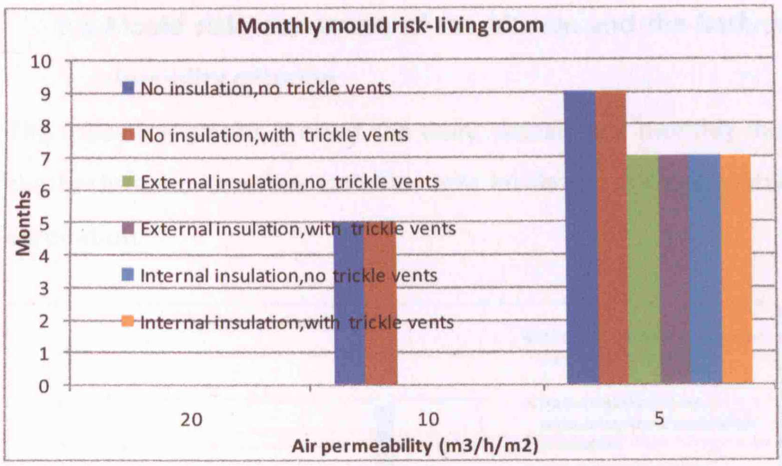


Figure 36: Monthly mould risk – living room

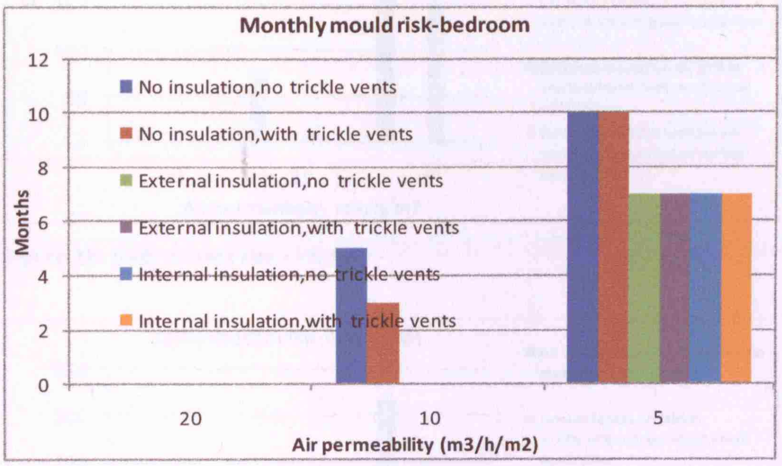


Figure 37: Monthly mould risk - bedroom

Evaluating the monthly mould growth risk, the general results are similar as with the weekly and daily mould risk.

To summarise, it could be said that for high values of air permeability (20 m^3/m^2h), there is no risk of mould no matter if insulation or trickle ventilators are used or not. For medium values of air permeability (10 m^3/m^2h), the use of insulation prevents mould growth, while for low values (5 m^3/m^2h), there is risk of mould growth for all the cases. The risk is greater for the uninsulated building. The use of trickle ventilators is effective only in medium air permeability and when there is no insulation. Finally, the position of the insulation does not have any influence on the mould risk, when this is assessed taking into account the relative humidity of the air. However, the effect of the insulation's position will be further explored later.

9.3. Mould risk assessment of the kitchen and the bathroom using the air's relative humidity criterion

The following graphs present the daily, weekly and monthly mould risk for the kitchen and the bathroom. Here the variables are: insulation, air permeability, and mechanical extract ventilation.

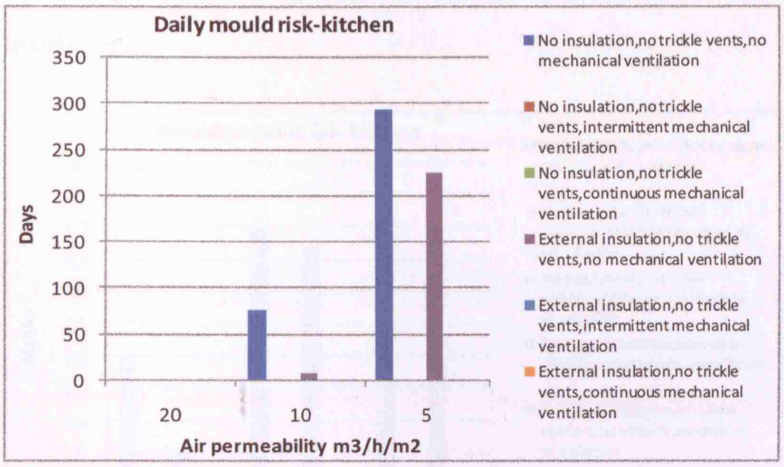


Figure 38: Daily mould risk - kitchen

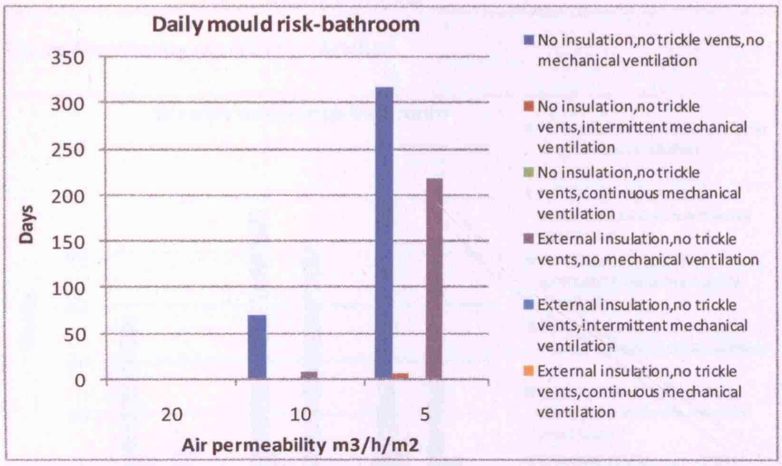


Figure 39: Daily mould risk - bathroom

The daily mould risk for the kitchen and the bathroom are similar. There is no risk when air permeability is high. As this value decreases, the risk of mould increases but only for the cases where there is no extract mechanical ventilation. For very low levels of air permeability, insulation has to be combined with mechanical ventilation so as to prevent the risk of mould. Also, it should be mentioned that the use of mechanical extract ventilation either intermittent or continuous, eliminates the risk of mould irrespective the existence of insulation.

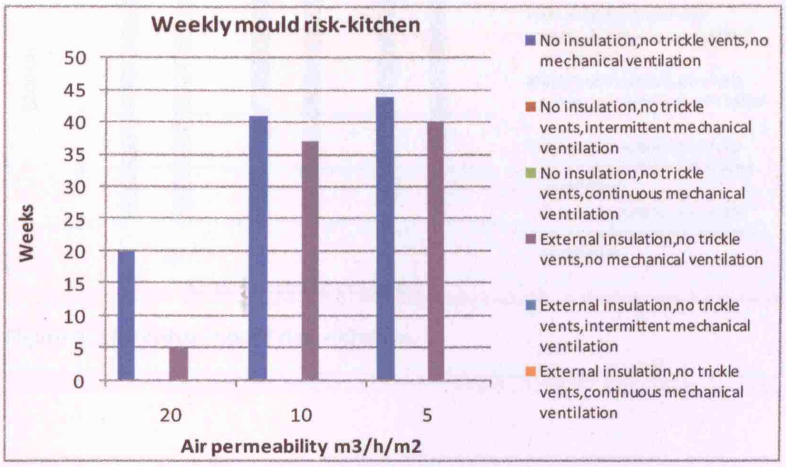


Figure 40: Weekly mould risk - kitchen

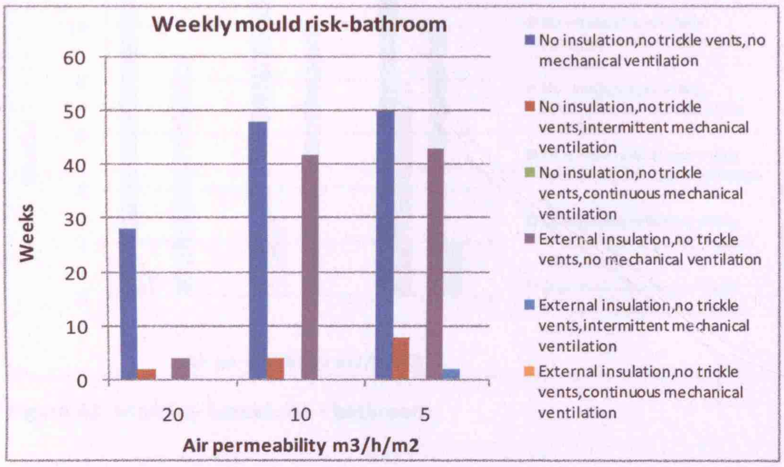


Figure 41: Weekly mould risk – bathroom

In weekly basis, for the case where there is no insulation and mechanical ventilation, the risk of mould increases as the air permeability decreases. However, the increase in the mould risk when the air permeability decreases from 10 m^3/m^2h to 5 m^3/m^2h, is much less than the increase of risk when the air permeability decreases from 20 m^3/m^2h to 10 m^3/m^2h. Also, the addition of insulation has greater effect at higher levels of air permeability. At lower levels the decrease in mould risk is much less with the addition of insulation.

It should be noted that at the bathroom, for the case where there is no insulation, but there is intermittent mechanical ventilation there is a small risk of mould which increases as air permeability decreases. Finally, when continuous mechanical ventilation is used there is no risk of mould regardless the existence of insulation or not.

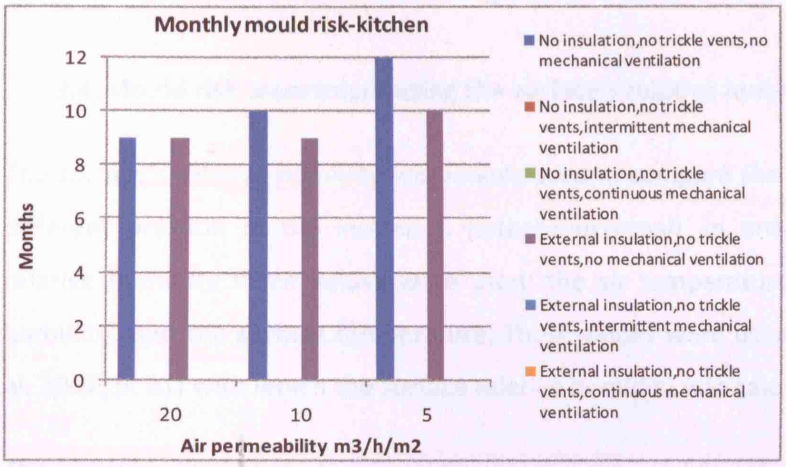


Figure 42: Monthly mould risk – kitchen

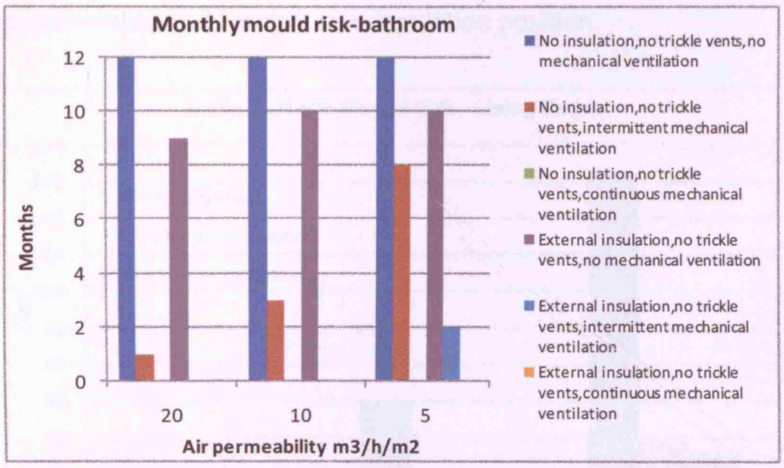


Figure 43: Monthly mould risk - bathroom

For the kitchen the average monthly relative humidity is higher than 70% for most of the months of the year when there is no mechanical ventilation. The addition of insulation slightly reduces the mould risk but only for lower values of air permeability. The use of mechanical ventilation (intermittent or continuous) eliminates the mould risk either there is insulation or not.

For the bathroom there is high risk of mould even when insulation is added. Furthermore, intermittent extract ventilation is not enough to prevent the risk of mould growth when there is no insulation. For the same case, the effectiveness of the intermittent extract ventilation decreases with the air permeability. However, when it is combined with insulation it eliminates the mould risk except for very low values of air permeability where there is still a low risk. On the other hand, the use of continuous extract ventilation is adequate to eliminate the mould risk regardless the existence of insulation.

9.4. Mould risk assessment using the surface's relative humidity criterion

The surface's relative humidity was mainly used to compare the effects on mould risk of the different position of the insulation (internal-external). In order to calculate the surface relative humidity three values were used: the air temperature, the 'damped' air relative humidity, and the surface temperature. These values were used in an algorithm (Palmer et al. 2007, p. 31) with which the surface relative humidity was calculated.

The critical values of relative humidity which were used to assess the risk of mould growth were 99%, 89%, and 80% for daily, weekly and monthly basis respectively (IEA 1990). The following figures present the daily mould risk for each space for different values of air permeability and for different insulation position.

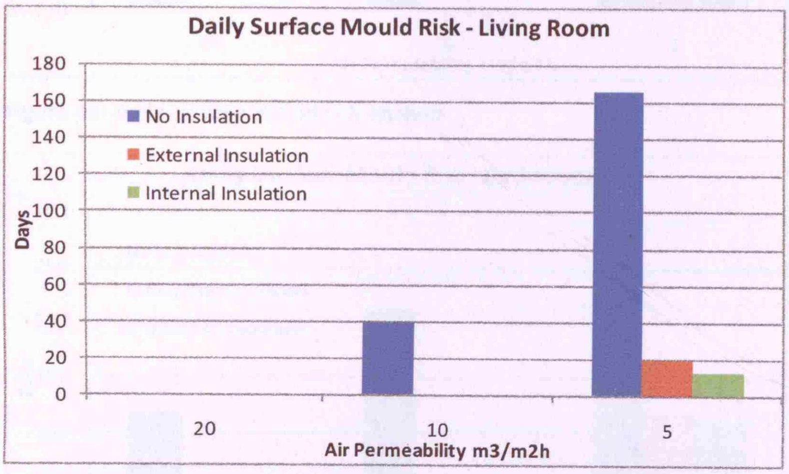


Figure 44: Daily surface mould risk-living room

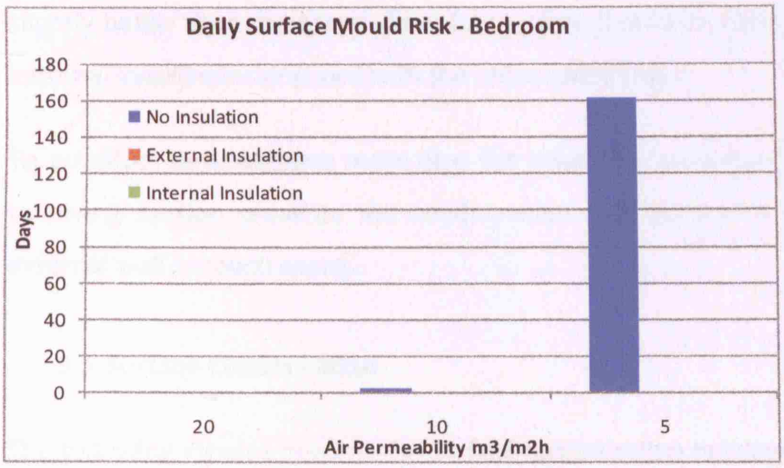


Figure 45: Daily surface mould risk-bedroom

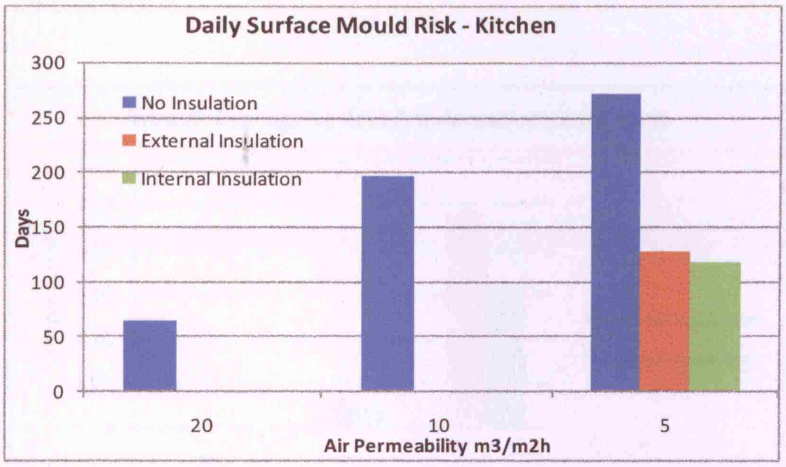


Figure 46: Daily surface mould risk-kitchen

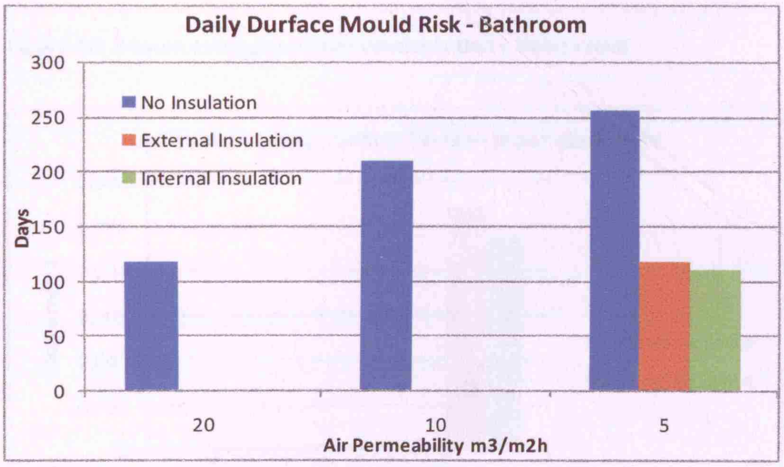


Figure 47: Daily surface mould risk-bathroom

For high and medium values of air permeability there is surface mould risk only when there is no insulation. With the insulation addition, there is surface mould risk only when the air permeability is 5 m^3/m^2h. Regarding the effect of the insulation position on the risk of mould growth using the surface relative humidity as criterion, it seems that internal insulation is slightly better than the external insulation since it reduces the mould risk 4%-5% more than external insulation compared with the uninsulated case.

To an effort to investigate more how the insulation position affects the risk of mould, the following section presents the condensation that occurs on the internal surface if the external wall for each space.

9.5. Surface Condensation

The following Figures present the surface condensation in kilograms/m^2. It should be noted that the results are taken directly from TAS. Consequently, they do not take account of the 'sponge effect'.

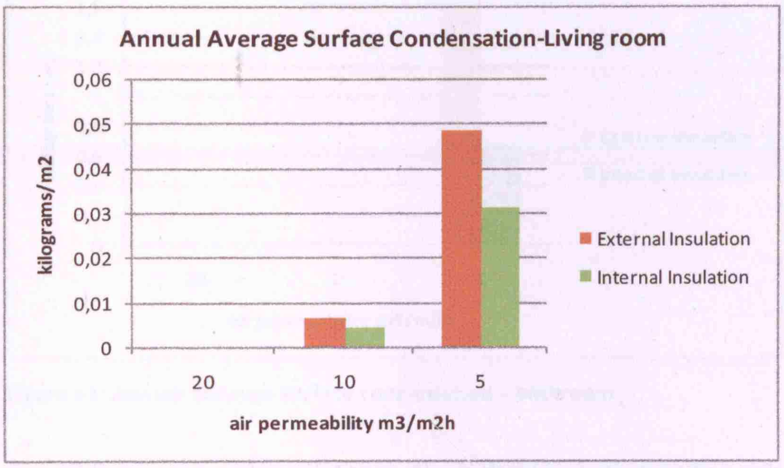


Figure 48: Annual average surface condensation – living room

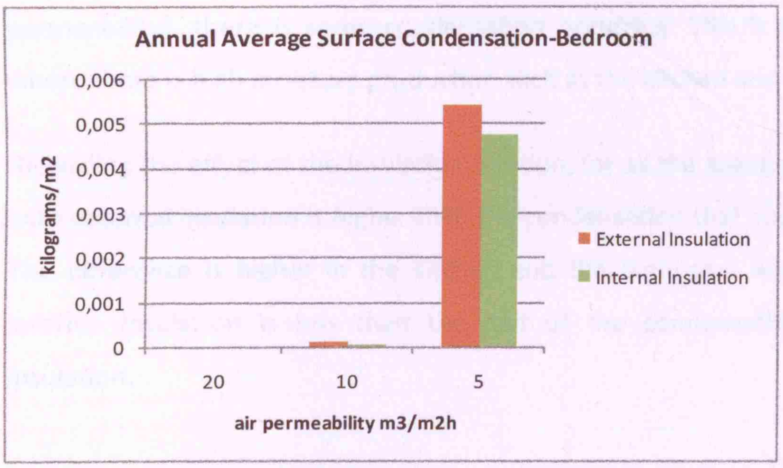


Figure 49: Annual average surface condensation – bedroom

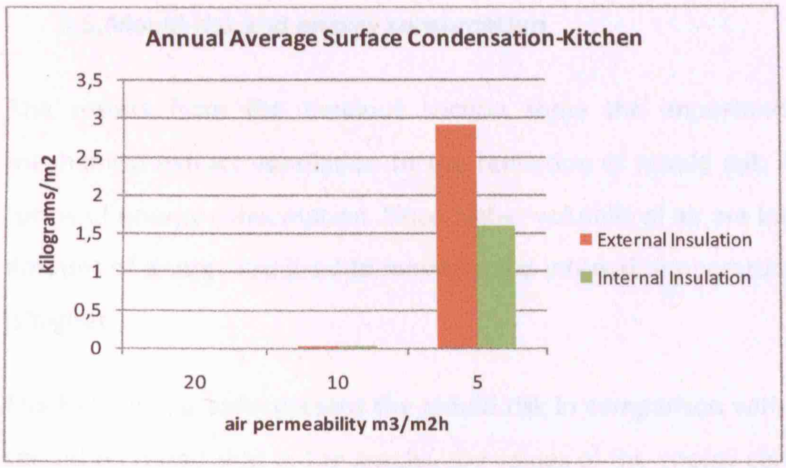


Figure 50: Annual average surface condensation – kitchen

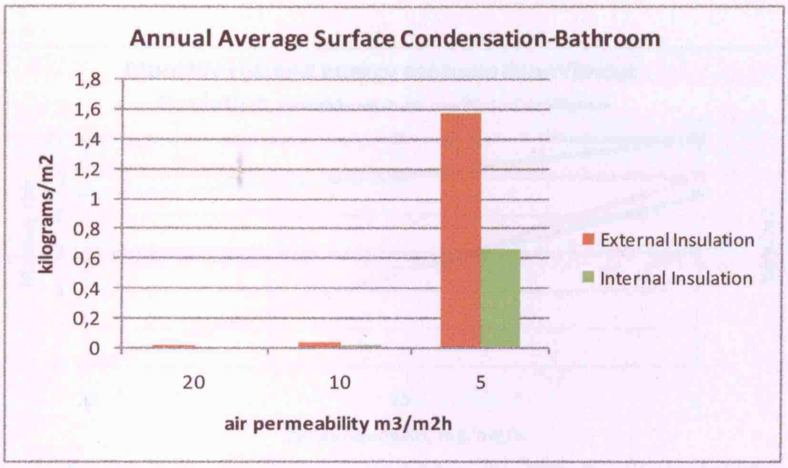


Figure 51: Annual average surface condensation – bathroom

For all the spaces, the existence of insulation eliminates the risk of surface condensation for high and medium air-tightness. However, when the air-tightness is high (5 m^3/m^2h air permeability), there is some condensation occurring. This is much higher in the spaces where there is high moisture production such as the kitchen and the bathroom.

Regarding the effect of the insulation position, for all the spaces, the resulting condensation with external insulation is higher than the condensation that occurs with internal insulation. The difference is higher in the kitchen and the bathroom where the condensation with internal insulation is less than the half of the condensation occurring with external insulation.

9.6. Mould risk and energy consumption

The results from the previous section show the importance of air permeability and mechanical extract ventilation to the reduction of mould risk. However, this has a cost in terms of energy consumption. Since higher volumes of air are introduced into the space, the amount of energy required to maintain the internal temperature within the desirable levels is higher.

The following graphs present the mould risk in comparison with the energy consumption. It should be noted that in the graphs, the values of the energy consumption are annual values for the whole flat and no for each space of the flat separately.

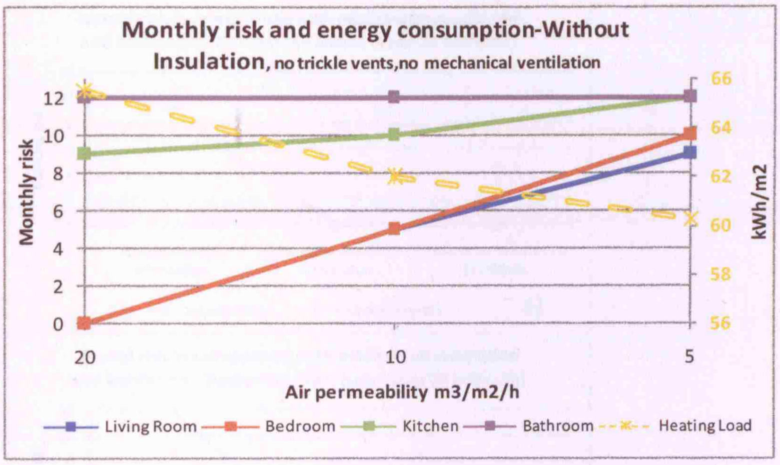


Figure 52: Monthly risk and energy consumption in relation with air permeability for the main spaces of the base case (no insulation, no trickle ventilators, no mechanical ventilation)

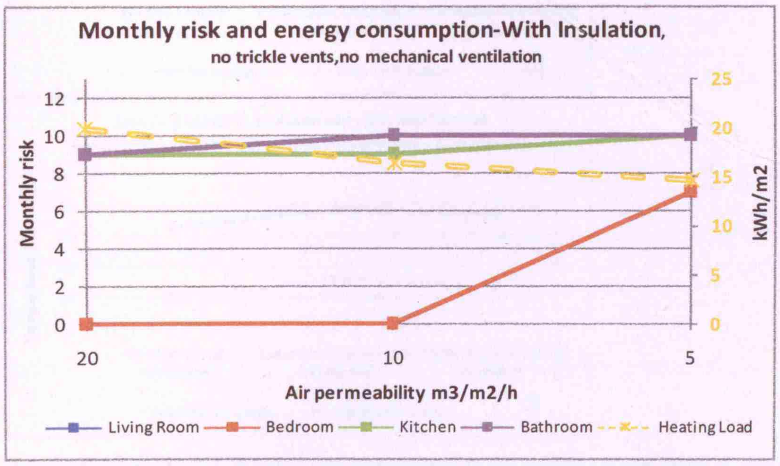


Figure 53: Monthly risk and energy consumption in relation with air permeability for the main spaces with added insulation (external insulation, no trickle ventilators, no mechanical ventilation)

Figures 52 and 53 clearly demonstrate the fact that the less airtight the construction is, the lower is the risk of mould growth and the higher are the energy demands. More specifically, for the uninsulated flat, the reduction in energy demands is about 10% (66kWh/m^2 for 20m^3/m^{2}h air permeability and 60kWh/m2 for 5 m^3/m^{2}h air permeability). The relative reduction when there is insulation is 5 kWh/m^2, which is equal with a 50% reduction in energy consumption. Furthermore, Figure 53 shows that the increase in mould risk is small for the rooms with high moisture production, while for the living room and the bedroom, the mould risk for 20 m^3/m^{2}h and 10 m^3/m^{2}h air permeability increases from 0 to 7 months for 5m^3/m^{2}h air permeability.

The following figures present the monthly mould risk of the kitchen and the bathroom and the effects on energy consumption in relation with insulation and the use of mechanical extract ventilation, for high (Figure 54) and low (Figure 55)levels of air permeability.

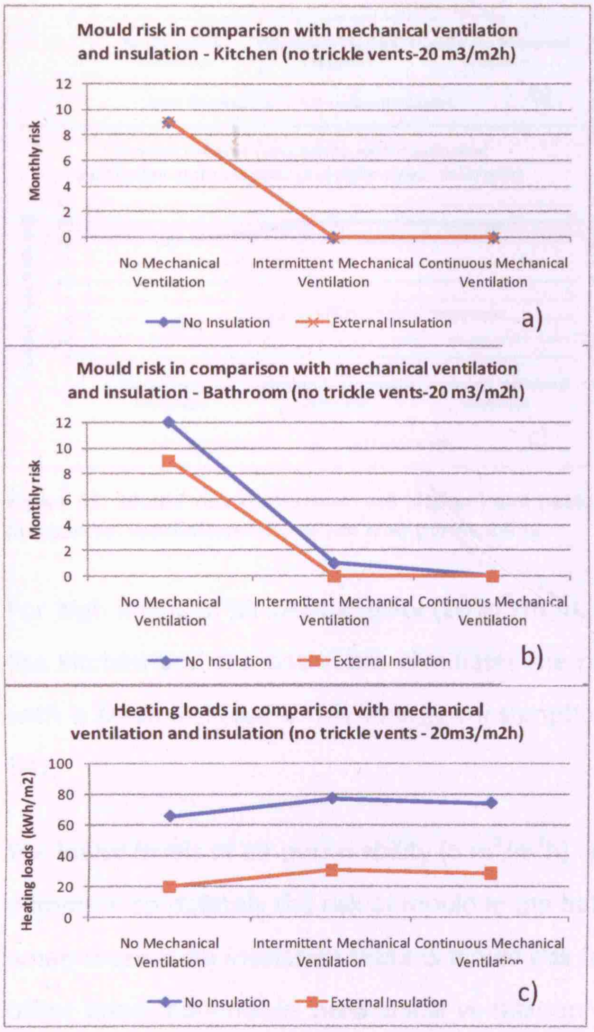


Figure 54: Mould risk (bathroom and kitchen) and heating loads (flat) in relation with insulation and with use of mechanical ventilation for 20 m^3/m^{2}h air permeability

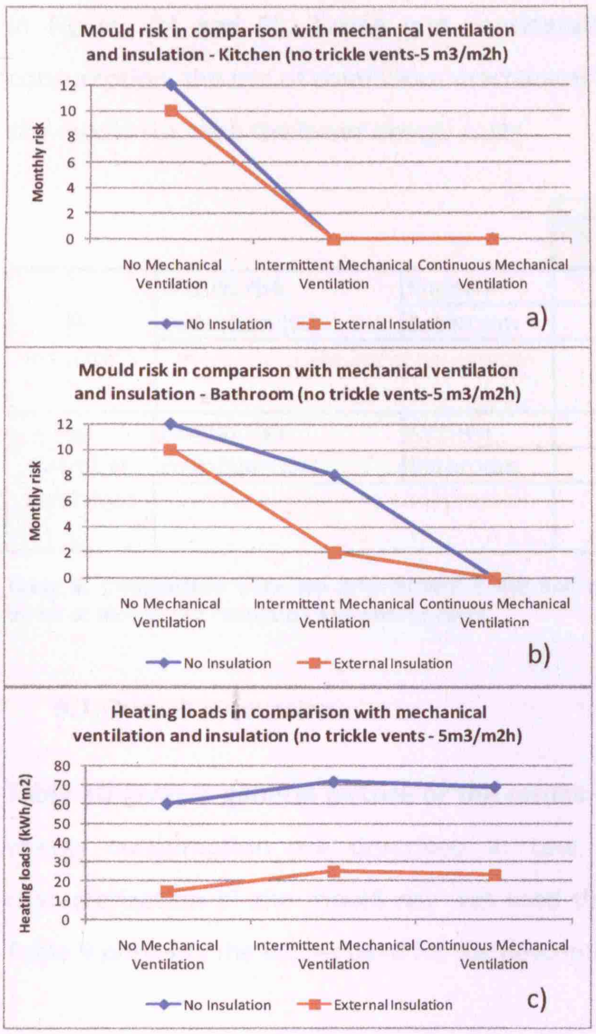


Figure 55: Mould risk (bathroom and kitchen) and heating loads in relation with insulation and with use of mechanical ventilation for 5 m^3/m^2h air permeability

For high levels of air permeability (20 m^3/m^2h), the use of mechanical extract ventilation in the kitchen and the bathroom eliminates the risk of mould. However, this is accompanied with a small increase in the energy consumption whether insulation is used or not (Figure 54).

For lower levels of air permeability (5 m^3/m^2h), intermittent mechanical ventilation does not eliminate completely the risk of mould in the bathroom even when there is insulation, while when there is no insulation there is mould risk for most of the months (Figure 55 b). On the other hand, continuous mechanical ventilation eliminates completely the risk of mould in the kitchen and in the bathroom regardless the existence of insulation (Figures 54 a),b) and 55 a),b) . Also when continuous mechanical ventilation is used, the heating loads are slightly lower than those when intermittent mechanical ventilation is used. The reason for this is the higher extract rate of the intermittent operation. Table 8 summarizes the results presented in Figures 54 and 55. Taking into consideration both the mould risk and the energy consumption, the use of continuous mechanical insulation is the best option as it eliminates the mould risk with the lower energy costs.

<table>
<tr><td></td><td></td><td></td><td colspan="2">High air permeability</td><td colspan="2">Low air permeability</td></tr>
<tr><td></td><td></td><td></td><td>IMV</td><td>CMV</td><td>IMV</td><td>CMV</td></tr>
<tr><td rowspan="3">No Insulation</td><td rowspan="2">Mould risk reduction (%)</td><td>Kitchen</td><td>100</td><td>100</td><td>100</td><td>100</td></tr>
<tr><td>Bathroom</td><td>92</td><td>100</td><td>33</td><td>100</td></tr>
<tr><td colspan="2">Increase in energy consumption (%)</td><td>18</td><td>13</td><td>19</td><td>14</td></tr>
<tr><td rowspan="3">External Insulation</td><td rowspan="2">Mould risk reduction (%)</td><td>Kitchen</td><td>100</td><td>100</td><td>100</td><td>100</td></tr>
<tr><td>Bathroom</td><td>100</td><td>100</td><td>80</td><td>100</td></tr>
<tr><td colspan="2">Increase in energy consumption (%)</td><td>53</td><td>44</td><td>71</td><td>58</td></tr>
</table>

Table 8: Comparison between intermittent (IMV) and continuous (CMV) mechanical extract ventilation in terms of mould risk reduction and energy costs.

9.7. Overall evaluation

Table 10 gives a general picture of the results of the simulations. The mould risk and the energy consumption are described as Low, Medium, High, and Very high. For the characterization of the mould risk was used the sum of the monthly risk for each space. Table 9 presents the values used for the description.

Energy consumption kWh/m2	Sum of the monthly mould risk	Description
0--20	0--12	Low
21--40	13--24	Medium
41--60	25--36	High
61--80	37-48	Very high

Table 9: Energy consumption and mould risk values description

Trickle Ventilators	Air Permeability at 50 Pa (m3/m2h)	Mechanical Ventilation	No Insulation		External Insulation		Internal Insulation	
			Monthly Mould Risk	Energy Consumption	Monthly Mould Risk	Energy Consumption	Monthly Mould Risk	Energy Consumption
No	20	No	Medium	Very high	Medium	Low	Medium	Low
	10	No	High	Very high	Medium	Low	Medium	Low
	5	No	Very high	High	High	Low	High	Low
Yes	20	No	Medium	Very high	Medium	Medium	Medium	Medium
	10	No	High	Very high	Medium	Low	Medium	Medium
	5	No	Very high	High	High	Low	High	Low
No	20	Intermittent	Low	Very high	-	Medium	-	Medium
	10	Intermittent	Medium	Very high	-	Medium	-	Medium
	5	Intermittent	High	Very high	Medium	Medium	Medium	Medium
Yes	20	Intermittent	Low	Very high	-	Medium	Low	Medium
	10	Intermittent	Low	Very high	-	Medium	Low	Medium
	5	Intermittent	High	Very high	Medium	Medium	Medium	Medium
No	20	Continuous	-	Very high	-	Medium	-	Medium
	10	Continuous	Low	Very high	-	Medium	-	Medium
	5	Continuous	Medium	Very high	Medium	Medium	Medium	Medium
Yes	20	Continuous	-	Very high	-	Medium	-	Medium
	10	Continuous	Low	Very high	-	Medium	-	Medium
	5	Continuous	Medium	Very high	Medium	Medium	Medium	Medium

Table 10: Overall evaluation of the mould risk and the energy consumption of each simulation

Table 11 provides a more accurate evaluation of the results. It presents the actual results from all the simulation in terms of energy consumption and mould risk (expressed as the sum of the monthly mould risk of each room) in increasing order of energy consumption.

Energy consumption kWh/m2	Mould risk (expressed as the sum of the monthly risk of each room)	Parameters of the simulations			
		Insulation	Air Permeability at 50 Pa (m3/m2h)	Use of trickle ventilators	Mechanical Ventilation (kitchen & bathroom)
15	34	External	5	No	No
15	34	External	5	Yes	No
15	34	Internal	5	Yes	No
15	34	Internal	5	No	No
16	19	External	10	No	No
16	19	Internal	10	No	No
20	18	External	20	No	No
20	18	Internal	20	No	No
21	20	External	10	Yes	No
21	20	Internal	10	Yes	No
22	24	Internal	5	Yes	Intermittent
23	16	External	5	No	Continuous
23	14	Internal	5	No	Continuous
23	10	Internal	10	Yes	Intermittent
24	20	External	20	Yes	No
25	18	Internal	20	Yes	No
25	16	External	5	Yes	Intermittent
25	16	External	5	No	Intermittent
25	0	External	10	No	Continuous
25	16	Internal	5	No	Intermittent
26	1	Internal	10	No	Continuous
27	0	External	10	No	Intermittent
27	0	Internal	10	No	Intermittent
27	9	Internal	20	Yes	Intermittent
28	14	External	5	Yes	Continuous
28	13	Internal	5	Yes	Continuous
28	0	Internal	20	No	Intermittent
29	0	External	20	No	Continuous
29	0	Internal	20	No	Continuous
30	1	External	10	Yes	Continuous
31	0	External	20	No	Intermittent
31	1	Internal	10	Yes	Continuous
32	0	External	10	Yes	Intermittent
33	0	External	20	Yes	Continuous
33	0	Internal	20	Yes	Continuous
35	0	External	20	Yes	Intermittent
60	43	No	5	No	No
60	43	No	5	Yes	No
62	32	No	10	No	No
64	30	No	10	Yes	No
65	21	No	20	No	No
68	21	No	20	Yes	No
69	19	No	5	No	Continuous
69	19	No	5	Yes	Continuous
70	10	No	20	Yes	Intermittent
71	11	No	10	No	Continuous
72	27	No	5	No	Intermittent
72	27	No	5	Yes	Intermittent
73	8	No	10	Yes	Continuous
73	14	No	10	No	Intermittent
74	0	No	20	No	Continuous
76	11	No	10	Yes	Intermittent
76	0	No	20	Yes	Continuous
77	1	No	20	No	Intermittent

Table 11: Actual energy consumption and mould risk for all the simulations.

The lowest values of energy consumption are about 15 kWh/m^2. However, the risk of mould for those cases is high. The lowest value of energy consumption for which the risk of mould is completely eliminated is 25 kWh/m^2. This occurs for the case of external insulation, without trickle ventilators, 10 m^3/m^{2}h air permeability, and use of intermittent extract mechanical ventilation in the kitchen and the value. It is also remarkable the role of the insulation in the significant reduction of the heating loads.

10. Mechanical Ventilation with Heat Recovery

The original intention of MVHR systems was to recover heat from the extracted air from a space. The heat recovery can be either direct or indirect (Figure 56). In mild climates, such as the UK's, the cost effectiveness of a MVHR system depends on a range of factors. These include the price of the fuel used for the system (and hence the value of the recovered heat), the level of the airtightness of the dwelling, the energy consumed by the fans, and the fact that in very airtight dwellings some form of continuous mechanical ventilation may be needed anyway.(BRE 1994)

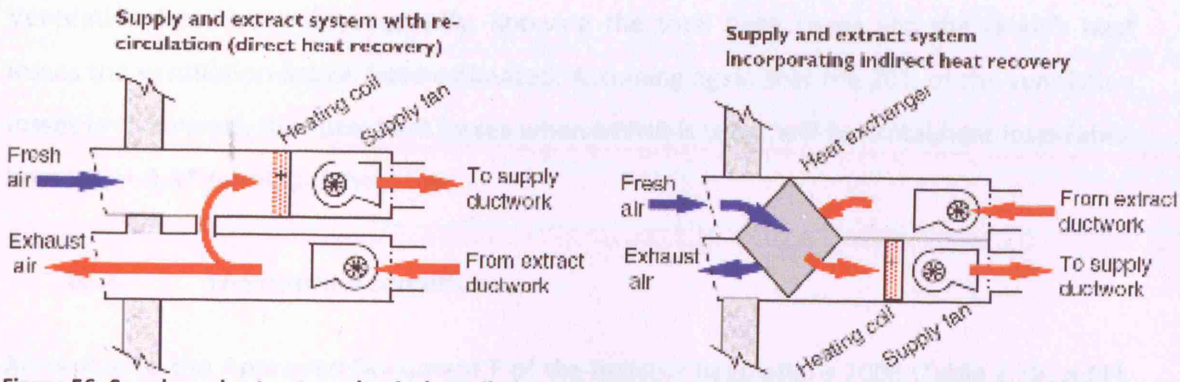


Figure 56: Supply and extract mechanical ventilation system with direct (left) and indirect (right) heat recovery (De Saulles 2002, p 21)

For optimum economic operation of the system, the dwelling must be as airtight as practicable. This means a background ventilation of about 0.2 ach. If this is achieved, the bulk of the dwelling ventilation will be provided by the mechanical ventilation system. (BRE, 1994)

In the studied case three different values of air permeability were studied. As mentioned in a previous section, even for hgh levels of air permeability (20 m^3/m^2h) the ach rate remains below the value of 0.2 ach due to the fact that the simulated flat has only two exposed facades.

10.1. TAS limitations

Because of the fact that TAS does not include an option for simulating a MVHR system, two different approaches were used.

Initially, it was assumed a 70% overall efficiency of the system. This means, that only the 30% of the air introduced by the mechanical ventilation system will have to be trated.

Hence, in TAS internal conditions, as input for the ach provided by mechanical ventilation was used the 30% of the real value. However, this would affect the level of the relative humidity. So, in order to overcome this problem, for each case two simulations were run. One with the reduced ach to predict the reduction in the heating load, and a second one with the normal ach rate to predict the level of relative humidity.

In the second approach, an initial simulation was run with 0 ach rate provided my mechanical ventilation in order to estimate the losses from the building's fabric (Fabric Heat Loss). A second simulation was also with the exact ventilation rate provided by the mechanical ventilation system. From this simulation the total heat loss from the building's fabric and from the ventilation system were estimated (Total heat loss = Fabric heat loss + Ventilation heat loss). Consequently, knowing the total heat losses and the fabric's heat losses the ventilation losses were estimated. Assuming again that the 70% of the ventilation losses is recovered, the total heat losses when MVHR is used, will be: Total heat loss=Fabric heat loss + 0,3*Ventilation heat loss.

10.2. TAS internal conditions

According to the Approved Document F of the Building Regulations 2006 (Table 1.1b, p.11), whole ventilation rate for the flat is 21 l/s (17 l/s for a 2 bedroom dwelling assuming 3 occupants + 4 l/s added for the fourth occupant). This is equivalent with a 0.35 ach rate provided by the mechanical ventilation system. The extract rate for the kitchen and the bathroom is the minimum high extract rate as defined in Table 1.1 a, p10 of the Approved Document F and it is 13 l/s for the kitchen and 8 l/s for the bathroom.

During the summer period it was assumed that only extract mechanical ventilation is used in the kitchen and the bathroom. The rest rooms are ventilated naturally by the opening of the windows.

10.3. Mould risk and energy consumption

Tables 12 and 13 present the mould risk using the air and the surface relative humidity correspondingly.

		Mould risk assessment using the air relative humidity criterion											
		Living Room			Bedroom			Kitchen			Bathroom		
	Air Permeability at 50 Pa (m3/m2h)	Daily Mould Risk	Weekly Mould Risk	Monthly Mould Risk	Daily Mould Risk	Weekly Mould Risk	Monthly Mould Risk	Daily Mould Risk	Weekly Mould Risk	Monthly Mould Risk	Daily Mould Risk	Weekly Mould Risk	Monthly Mould Risk
No Insulation	20	0	0	0	0	0	0	0	0	0	0	0	0
	10	0	0	0	0	0	0	0	0	0	0	0	0
	5	0	0	0	0	0	0	0	0	0	0	0	0
External Insulation	20	0	0	0	0	0	0	0	0	0	0	0	0
	10	0	0	0	0	0	0	0	0	0	0	0	0
	5	0	0	0	0	0	0	0	0	0	0	0	0
Internal Insulation	20	0	0	0	0	0	0	0	0	0	0	0	0
	10	0	0	0	0	0	0	0	0	0	0	0	0
	5	0	0	0	0	0	0	0	0	0	0	0	0

Table 12: Mould risk assessment using the air relative humidity criterion

		Mould risk assessment using the surface relative humidity criterion											
		Living Room			Bedroom			Kitchen			Bathroom		
	Air Permeability at 50 Pa (m3/m2h)	Daily Mould Risk	Weekly Mould Risk	Monthly Mould Risk	Daily Mould Risk	Weekly Mould Risk	Monthly Mould Risk	Daily Mould Risk	Weekly Mould Risk	Monthly Mould Risk	Daily Mould Risk	Weekly Mould Risk	Monthly Mould Risk
No Insulation	20	0	0	0	0	0	0	0	0	0	0	0	0
	10	0	0	0	0	0	0	0	0	0	0	0	0
	5	0	0	0	0	0	0	0	0	0	0	0	0
External Insulation	20	0	0	0	0	0	0	0	0	0	0	0	0
	10	0	0	0	0	0	0	0	0	0	0	0	0
	5	0	0	0	0	0	0	0	0	0	0	0	0
Internal Insulation	20	0	0	0	0	0	0	0	0	0	0	0	0
	10	0	0	0	0	0	0	0	0	0	0	0	0
	5	0	0	0	0	0	0	0	0	0	0	0	0

Table 13: Mould risk assessment using the surface relative humidity criterion

The use of continuous mechanical ventilation for the whole flat with heat recovery eliminates the risk of mould in all cases. The next step towards the viability of the MVHR system is the evaluation of the cost in terms of energy consumption for heating (Table 14).

		Parameters of the simulations	
Energy consumption kWh/m2	Mould risk (expressed as the sum of the monthly risk of each room)	Insulation	Air Permeability at 50 Pa (m3/m2h)
19,5	0	External	5
19,5	0	Internal	5
21,3	0	External	10
21,3	0	Internal	10
24,9	0	Internal	20
25,0	0	External	20
65,4	0	No	5
67,1	0	No	10
70,6	0	No	20

Table 14: Energy consumption for the simulations which included MVHR

The lowest energy consumption is occurring for the lowest value of air permeability, something which indicates the importance of air-tightness when mechanical ventilation system with heat recovery is used. The energy requirements for when either external or internal insulation is used, is 19.5 kWh/m^2.

This value is even lower than the value of the 25 kWh/m^2 (external insulation, 10 m^3/m^2h, continuous extract mechanical ventilation in the kitchen and the bathroom, Table 11), which is the lowest amount of energy required to achieve elimination of mould risk when MVHR is not used.

11. Conclusions

The results of the study indicate that the most efficient way of dealing with the risk of mould growth is the use of mechanical ventilation with heat recovery (MVHR) as the aim of eliminating the mould risk is achieved with minimum energy consumption. However, if the system is to be economically efficient it should be accompanied with the improvement of thermal performance of the building's fabric. Here, it should be highlighted the importance of two parameters that can have an important effect on the overall performance of the system. The first one is the air-tightness of the dwelling. The more air tight the construction is, the less will be the infiltration losses and consequently the amount of the recovered heat will be higher. Secondly, the occupants should be adequately informed about the operation of the system since their behavior can affect the performance of the system in a great extent. The refurbishment of the Lodge Lane at Croydon is a real example of such a case.

The role of the insulation is essential for the improvement of the thermal performance of any building. For the aims of the study, despite the many options, the simulation included only two types of insulation. Internal insulation and render finish external insulation. Both of them had similar results in terms of reduction of the energy consumption and also in terms of the resultant relative humidity of the air. In an effort to investigate the role of the position of the insulation on the mould risk it was calculated the relative humidity of the external walls' surface. The results were very similar with the mould risk being slightly lower for the case of internal insulation. However, it was also estimated the surface condensation for each case. The results for the internal insulation were 30%-50% lower than those for the external insulation. It should be noted here though, that these results were taken directly from TAS and the moisture absorption by the walls were not taken into consideration.

In terms of mould risk reduction, the insulation itself is not enough to prevent completely the risk of mould growth. This is achieved only when the insulation is combined with some form of mechanical ventilation (extract intermittent or continuous mechanical ventilation, or whole flat mechanical ventilation with heat recovery).

Comparing the two patterns of mechanical extract ventilation (intermittent, continuous) in the rooms with high moisture production (kitchen, bathroom), the use of CMV is more efficient that the use of IMV. The risk of mould is less in most of the cases while, the energy losses are almost the same. It should be noted here that the extract rate for the IMV is higher than that for the CMV (According to the Approved Document F of the Building Regulations).

In new buildings and refurbishments projects as well, airtightness is considered to be one of the most important factors towards the effort of achieving reduced energy consumption. If the construction is too tight the infiltration heat losses are reduced, however, the risk of mould growth is increased. In air-tight constructions, if mould is to be avoided, there must be an adequate ventilation pattern. The most appropriate solutions for these cases is the use of mechanical ventilation with heat recovery.

Trickle ventilators are mainly used to provide background ventilation during the heating period were the opening of the windows for ventilation purposes is not possible due to high energy losses. The equivalent area of trickle ventilators was 40,000 mm^2 which complies with the Part F of the Building Regulations. The simulation results showed that their contribution to the mould risk is relatively small, and only for the case where there is no insulation. Trying to investigate the reasons for this, it was checked in TAS the air flow rates through the trickle ventilators. The outcome was that there was not any air flow through the trickle ventilators, and if there was, it was only during the summer months (Figure 57). The reason for that could be possibly attributed to the fact that the trickle ventilators were simulated as windows which were constantly open in combination with their small area.

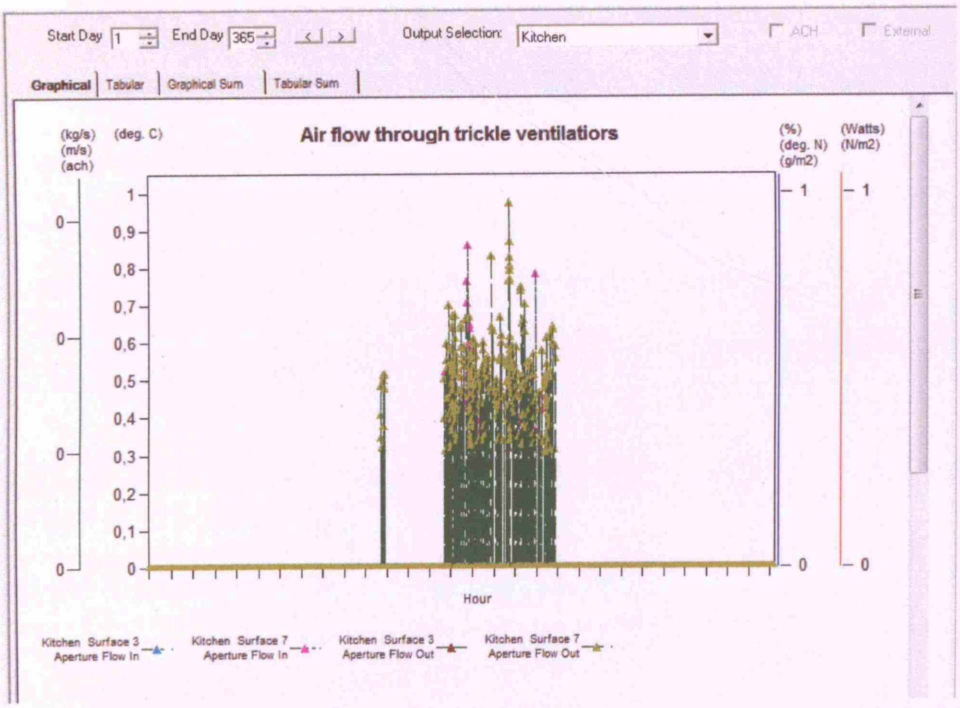


Figure 57: Air flows through trickle ventilators of the kitchen for the case of no insulation and 20 m^3/m^2h air permeability

In terms of cost, the use of cavity wall insulation is the most efficient. However, for high-rise buildings a feasibility study should always be conducted as this type of insulation might have implications. The most usual and at the same time the most expensive refurbishment method of the building's fabric is the overcladding. However, the improved external appearance of the building is the main advantage of this option. Finally, internal insulation is commonly used when intervention at the external façade of the building is not feasible.

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